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FUEL TAXES, MOTOR VEHICLE EMISSION STANDARDS AND PATENTS RELATED TO THE FUEL-EFFICIENCY AND EMISSIONS OF MOTOR VEHICLES

Joint Meetings of Tax and Environment Experts

This paper was prepared by Herman Vollebergh of Netherlands Environmental Assessment Agency, as a contribution to the project on Taxation, Innovation and the Environment of OECD's Joint Meetings of Tax and Environment Experts. It studies the impacts of motor vehicle fuel taxes and mandatory fuel efficiency standards on relevant car-related innovation activity in selected car-producing countries.

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FOREWORD

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FUEL TAXES, MOTOR VEHICLE EMISSION STANDARDS AND PATENTS RELATED TO THE FUEL-EFFICIENCY AND EMISSIONS OF MOTOR VEFHICLES

1. Introduction

- 1. This paper explores the technology-stimulating impacts of different policy instruments. Using patent data for a representative set of 19 OECD countries between 1965 and 2005, we study to what extent patent filings by inventing firms are sensitive to the use of different policy instruments in different countries. In this study, we bring together patent data on technologies that improve fuel efficiency of cars and abate specific emissions, and relate them to regulatory interferences, such as car exhaust standards and fuel taxes. The interaction is particularly complicated, because a whole set of pollution emissions is associated with motoring (in particular cars and trucks), such as NO_x, HCs, VOCs, lead, sulphur, Particulate Matter (PM) and CO₂. In particular, we focus on countries that host car-producing firms (like US, France, Germany, Italy, Japan, Sweden, etc.). To what extent patenting by firms in these countries is also triggered by other countries' regulation, is another issue worth analyzing in this international context.
- 2. Accordingly, this study fits into a relatively small literature that explicitly analyse the differential impacts from different types of environmental policy instruments on technological change (Vollebergh, 2007/OECD, 2007). For a long time, comparisons have only used indirect evidence, because of the lack of market-based instruments in practice and/or the availability of data to evaluate them. In particular, several studies have looked at a differential impact using energy prices as a proxy for variation in the stringency of market-based instruments. According to this idea, a rise in the energy price is likely to shift technological change towards less energy-intensive technologies, the use of which, in turn, also reduces emissions as long as energy and emissions are complements. In particular, several studies have used hedonic price functions to examine the effects of public policy, for instance in the contexts of home appliances and of the energy efficiency of cars.
- 3. Our study is closest to Newell, Jaffe and Stavins (1999), who used a product-characteristics approach to evaluate the relative impact of energy prices and changes in energy-efficiency standards. This approach captures the important effect of invention creating new 'models' with characteristics not previously feasible, and of innovation commercializing models that were not previously offered for sale. In this study we look for changing characteristics of cars in response to environmental and tax policy, measured by their likely impact on the number of patents filed for different types of technologies that would match the concerns of the policy makers. Accordingly, we bring Popp's (2002) seminal contribution to the field of car-makers and their responses to different types of instruments.
- 4. Closely related work to date is De Vries (2007) and also Crabb and Johnson (2007). The main focus of the paper by De Vries (2007) is the channel which separates emissions from input use (gasoline, diesel) and output (car use), *i.e. emission abatement*. We not only use another database that is particularly useful for international comparisons, but also expand his analysis to fuel efficiency measures as well as

According to this approach, induced innovation is the movement in the frontier of feasible models that reduce the cost of energy efficiency in terms of other attributes [see Newell *et al.* (1999), pp. 943ff].

measures related to the characteristics of the fuels used. Furthermore, we use a much better suited patent count than Crabb and Johnson (2007), who also only focused on US patents.²

5. In the next section we discuss our framework of analysis. Section 3 describes in more detail which patents for conventionally fuelled motor vehicles matter to control emissions and fuel efficiency. Also relevant patent selection is described in more detail. Section 4 provides a detailed description of the set of most important regulatory interventions (including petrol taxes) by different OECD governments, in particular European Commission, Japan and USA. Section 5 describes our patent counts. In Section 6 we first introduce our econometric approach and then present our main results for a subset of countries, in particular Germany, Japan and the USA. Finally, Section 7 concludes.

2. Background

2.1 Linking environmental policy to technological change

- 6. That environmental policy is of critical importance to the inducement and diffusion of new technologies ('technological change' for short) is hardly disputed nowadays (OECD 2007/Vollebergh, 2007). Economists long ago pointed at what they called the potential dynamic effects of environmental policy. Kneese and Schulze (1975) even claimed that one of the most important criteria on which to judge the performance of environmental policy instruments is the extent to which they spur new technology toward the efficient conservation of the environment. Accordingly, one would expect environmental stringency through emissions restrictions, other than by output reduction or factor substitution, to also be a fundamental driver of an increase in research and development (R&D) investment in abatement technologies, subsequent filings of new patents and, finally, a reduction in emissions. A relatively recent and new literature is precisely concerned with demonstrating these effects empirically.
- Economists also believe that changes in incentives in the background are indispensable. In particular, environmental policy, whether through emissions restriction legislation, changes in (specific) taxes, subsidies or even tradable permits (TDP), is often considered to be an important prerequisite for firms and households to develop and adopt new equipment or technologies with more environmentally favourable characteristics. If incentives matter, one would also expect different policy instruments to have different effects on the rate and direction of technological change. Indeed, economists generally believe that so-called market-based instruments can provide stronger incentives than command and control (CAC) regulations to adopt cheaper and better pollution-control technologies. First, CAC policies, such as emissions prescriptions for installations, provide no reward for exceeding the requirements set by the regulations. However, under a market-based policy, firms that perform better than is required by such regulations face continuous rewards, because their tax payment can be lowered or they could sell excess pollution permits. Moreover, direct regulations constrain the potential 'space' for innovation, reducing incentives to identify those options that are most cost-effective in the long run. Standards imposed under command-and-control (CAC) also provide clear signals as to what engineering characteristics of production processes are undesirable and this, in turn, is likely to be targeted by inventors. Standard-driven technological change is directed by the precise signal given by the standard (see Helfand, 1991).³ In addition, the choice of the tax-base of a specific regulatory tax, i.e. a tax per unit emission or fuel characteristic, also provides such signals to inventors (Keen, 1998). If technologies or product

While the work of Crabb and Johnson (2007) is a good starting point (after applying appropriate USPC-IPC concordance tables), their search strategy is not very convincing (see OECD, 2007/Vollebergh 2007)

As such, standards which target *the environmental externality* directly are likely to be more efficient than less targeted standards.

characteristics are mutable, inventors can create new technologies or product designs that reduce the tax impact.⁴

- 8. So far, the focus in the literature on substitution channels is mainly based on models using comparative statics. Keen (1998), for instance, studied the differences in incentive effects from *ad valorem* vs. specific taxes and Parry and Small (2005) studied different substitution channels based on differences in tax design of motoring. The aim of the present study is to explore whether such channels also add a dynamic component. In particular, we study to what extent inventors are triggered and by what instrument in particular.⁵
- 9. The effects of these policies on different emissions can be complicated, however. In general, there are potentially complicated interactions between policies targeted on different pollutants. Several aspects need to be considered:
 - Pollutant-by-pollutant regulation can induce engineering trade-offs and hence may lead to perverse effects (*e.g.* emission standards for NO_x may actually increase fuel consumption, and thus CO₂ emissions);
 - Type of policy instrument generally differs by emission emission standards (CO, HC, NO_x, PM) vs. fuel taxes (CO₂ indirectly, sulphur and lead in some cases);
 - The inter-relationship between different variables of interest, such as the additive effects of pretax fuel prices and fuel taxes, and the joint use of policy measures to achieve comparable objectives (e.g. fuel taxes and efficiency standards).

2.2 Substitution mechanisms triggered by regulation in a static setting

10. To assess the likely impacts of environmental policy measures on innovation, it is useful to distinguish, first of all, explicitly between the incentive mechanisms induced by different types of regulation in a static setting, before considering generalizations to a dynamic setting.⁶ As a starting point, consider the following substitution channels to evaluate different taxes or standards from a regulatory perspective:

- First, end-of-pipe *emission abatement* separates emissions entirely from input use and output;
- Second, *input substitution* implies the substitution of emission-intensive for emission-extensive inputs, like switches in the composition of fuels used;
- Third, *factor substitution* involves the replacement of dirty by clean inputs, such as capital for energy;

The significance of this mutability is illustrated by efforts of the (German) automobile industry to argue in favour of a fuel tax per kg of carbon emitted instead of energy-content. Recent innovations in diesel engine technology in the German industry render next-generation diesel cars much more fuel efficient (fuel use per kilometre driven). Diffusion of this technology would be greatly enhanced by a tax that puts less weight on fuel content but more on kilometres driven, because diesel cars drive longer distances per unit fuel.

Greene (1990) showed that the CAFE standards introduced by the US government also had an effect, in particular for US automobile manufacturing firms. He estimated that the CAFE constraint was binding for US-based firms and not for foreign (European and Japanese) firms. Specifically, CAFE standards had perhaps twice as much influence as gasoline prices.

This section draws on Smulders and Vollebergh (2001), who studied the efficiency of differences in tax design, allowing for mutability of carbon use in production processes.

- Fourth, *output substitution* accounts for the substitution between dirty and clean products, and also includes what could be called *output characteristics substitution*, applying to changes in the characteristics of products.
- 11. Taxes or standards typically differ as to what and how these different mechanisms are triggered. The tax- or regulatory- base chosen has significant implications for the incentives to exploit these four options. The first option is regulation of *emissions*, for instance through the Pigouvian prototype tax. Such a tax prices emissions directly. As a result, a profit-maximising firm is likely to search for substitutionoptions that reduce tax payments. If emission abatement options are available, the least distorting option is to implement such technologies, as long as they are cost-efficient. Another option for a firm is to substitute away from emission-intensive inputs to emission-extensive inputs, because it also reduces emissions and therefore reduces tax payments. This incentive mechanism is less direct and distortions are likely to be larger for the firm. However, as long as this mechanism contributes to cost-efficient emission abatement at the margin, the agent is likely to exploit this channel, in addition to emission abatement. An even less direct option is substituting energy-extensive for energy-intensive technologies which also reduce emissions, as long as they are linked to energy use. A final option is the reduction of output, which is likely to be the most costly, given its usually very indirect link with emissions. The prototype Pigouvian emission tax exploits all four mechanisms at the same time, explaining its efficacy (and, by implication, its emission-reduction efficiency).
- 12. The alternative of *input* regulation, like a tax or standard on energy, does not exploit the emission abatement channel of reducing emissions, however. With input taxation, for instance, the firm can no longer reduce tax payments directly by reducing emissions, if this would require the same (or more) inputs. Obviously, the input channels can be exploited in this case, but which of the two input substitution mechanisms is triggered depends on the choice of the input tax rate and the technological options available. An *ad valorem* input tax, for instance, only changes the relative input prices between dirty and clean inputs. With an input tax that also reflects differences in input characteristics, like differences in sulphur or lead content, substitution within an input composite will be triggered.
- 13. Finally, *output* regulation can also be exploited as an alternative for an emission tax. For instance, an *ad valorem* output tax is a very indirect and therefore a costly instrument to reduce emissions. A firm facing an output tax has no incentive to abate emissions directly, because this does not contribute to a lower tax burden. The efficiency of the output tax entirely depends on the (very indirect) link between output and emissions. In this case, output taxes are clearly inferior to emission taxes, where firms also are induced to consider all channels to reduce emissions. However, with a *specific* output tax-base, *i.e.* with a tax-base linked to the goods' characteristics, an output tax also induces firms to reconsider their product composition as long as it is mutable, providing the firm with emission reduction opportunities with potentially low cost.
- 14. Both standards and taxes are rather similar depending on which is the point of incidence of the measure serving an analogous role to the tax-base. Performance standards which target the emission directly have the potential to induce all four strategies. Conversely, depending upon how it is formulated, a technology-based standard may not provide incentives for one or more of these channels. More generally, however, in a dynamic context, standards (even if targeted directly on the externality) will not provide continuous incentives for innovation. Once a given standard has been met, there is no incentive to reduce emissions further, unless doing so triggers a response from the regulator.

2.3 Substitution mechanisms in a dynamic setting

15. The classification of substitution mechanisms in a static setting identifies options for firms to react to different types of policy measures. This analysis typically classifies substitution channels along a

given technology frontier, however, which implies – conceptually – that these substitution mechanisms only exploit already known and available products or technologies. Accordingly, the focus is on the promotion of their diffusion. In other words, these mechanisms represent shifts along the technology frontier, but they do not describe shifts of the frontier. Dynamic incentives proper represent entirely new technologies that may or may not be implemented in practice.

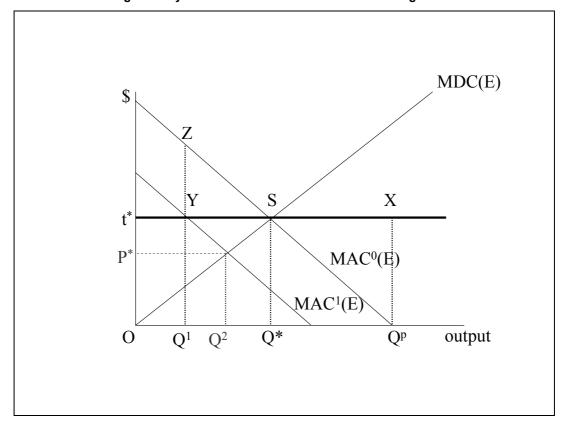


Figure 1. Dynamic incentives from environmental regulation

16. Economists strongly agree that different types of regulation matter for the rate and direction of technological change. Why one might expect a differential impact of environmental policy instruments on technological change can now easily be understood using Figure 1. This figure illustrates technological change as an *inward shift of* the marginal abatement cost curve (MAC), and therefore clearly represents a shift *of* the (abatement) technology frontier. The idea behind this shift could be explained as follows. Assume profit-maximizing firm produce output Q^p in the *status quo* and face the introduction of a tax t* on their emissions to internalize the marginal damage associated with production (MDC). Then the firms may avoid paying the full *initial* tax amount Ot*XQ^p by reducing waste or adopting currently available and relatively inexpensive add-on technologies, described by the marginal abatement cost curve MAC⁰(E). Equivalent incentives could be expected from a CAC regulation that forces the firms to adopt this technology and produce at Q*. With a tax or (yearly) auctioned tradable permits (TDP), the firms still face additional payments equal to 0t*SQ*.

frontier as described by Newell *et al.* (1999). Less elastic abatement in the *status quo* corresponds to few options to reduce emissions without reducing output. New inventions are likely to make abatement more elastic, whereas learning is typically more linked to diffusion processes rather than new inventions.

Note that the inward shift of the marginal abatement curve is exactly similar to the shift in the technology frontier as described by Newell et al. (1999). Less elastic abatement in the status quo corresponds to few

- 17. To avoid paying for the remaining emissions infinitely, these firms could also invest in invention or innovation to develop new abatement equipment with lower remaining emissions and therefore lower tax payments. If successful, the production possibility set is shifted *outwards* (higher emissions abatement for a given input), which would induce an *inward* shift of the abatement cost curve (lower costs per unit of emissions abated). Such an abatement cost curve, like MAC¹(E), reduces tax payments substantially, to Ot*YQ¹. So it would always be profitable for the firms to try to make the invention as long as the expected (average) costs of the new investments (plus the cost of any capital equipment the technology requires) is lower than the (average) tax savings Q¹YSQ*.
- 18. Such incentives for invention and innovation do not exist if a firm does not expect future CAC regulations to be stricter than those currently applied, say at the level of Q*. If firms comply with the current regulations and abatement costs MAC⁰(E) are 'sunk', no additional benefits can be expected from investing in new abatement equipment labelled MAC¹(E).
- 19. Looking at patents provides insight in innovative firms and how they anticipate or react to changes in their regulatory environment. The detailed information contained in patents allows one to trace back disembodied knowledge flows between countries. Using differences in timing of patenting behaviour as induced by different types of regulatory interventions, one is able to identify the differential effect of instruments on technological change and the international diffusion of knowledge flows. New patents indeed have the potential to shift the technological frontiers in practice.

2.4 Environmental regulation and technological change in the automobile sector

- 20. This study looks at how different environmental regulations trigger decisions by car-making firms to invest in new products or processes. In other words, new technologies can be expected from regulation that addresses major pollutants emitted by motor vehicles: carbon monoxide (CO), hydrocarbons (HCs), nitrogen oxides (NO_X), particulate matter (PM), lead (Pb), sulphur dioxide (SO₂) and volatile organic compounds (VOCs). In the automobile sector, the relevant *new* technologies or products would involve not only changes in petrol and diesel engines of cars, but also cars driven by entirely new engines, as well as changes in the design of the cars to increase fuel efficiency.
- 21. The focus in the paper is on patents as an *observable* output-indicator of R&D activities related to innovation within the automobile sector. The assumption is that environmental policy whether this is through a standard or a specific tax signals to (new) producers that it is beneficial to be engaged in dedicated R&D to meet the requirements of the standard or to reduce tax payments. If this is indeed the case, one would expect a rise in R&D activity specifically dedicated to the invention of new technologies (products) or the improvement of existing ones addressing the concern as signalled by the regulatory device. For the identification of inventions, one might look at the development of different types of new technologies (see Popp, 2002) or product characteristics (Newell, Jaffe and Stavins, 1999). 10
- 22. In line with the substitution mechanisms explained in the previous section, inventions relevant for vehicle fuel efficiency and local air pollution emissions abatement are classified in the following areas:

Note that the graph disregards the potential of selling the technology to other firms in a similar situation (and therefore implicitly focuses only on in-house inventions, not on incentives for *e.g.* producers of capital equipments to develop better technologies for their clients).

Measuring invention of new technologies through patents also has drawbacks. For instance, firms may not always patent to protect their rents or may 'over-patent', as strategic deterrence (Cohen, Nelson and Walsh, 2000; Jaffe and Trajtenberg, 2002).

Note that the difference between specific technologies could also be understood as a product. What matters is that the output bundle is described by its (input and/or output) *characteristics*.

- First, typical end-of-pipe *emission abatement* for cars are post-combustion (after-treatment) devices that reduce the amount of emissions per km driven, like catalytic converters, lowering tailpipe emissions (*e.g.* NO_x);
- Second, *input substitution* is typically related to the characteristics of the fuels and the additives used to enhance productivity and emission intensity of the combustion process; development of alternative fuel vehicles, such as biofuel-driven, hydrogen-based or electric cars are other examples of this type of substitution involved;
- Third, we approach *factor substitution* here through technologies that typically involve engine redesign, *e.g.* through the introduction of combustion technologies that require less fuel per kilometre driven and therefore reduce emissions per km;
- Fourth, *output substitution* for petroleum-based cars is typically linked to measures primarily designed to improve *fuel efficiency* through alternative design of cars, like their aerodynamics, or other characteristics, such as tyre resistance, but also substitution of materials to decrease weight.
- 23. With hindsight, we know that regulation has not resulted in major shift away from the combustion engine for cars. Instead, conventionally-fuelled vehicles are still by far the most important type of car. Therefore our focus is primarily on conventionally-fuelled vehicles, and on how car-making firms have responded by retrofitting and re-engineering these combustion engines. However, we also include patents that allow for mutability of inputs, such as changes in the composition of the fuel blends as well as measures to improve fuel-efficiency of cars in general.

3. Patents for conventionally fuelled motor vehicles

3.1 Technologies to increase fuel efficiency and emissions control

- 24. With our focus on conventional fuel-driven cars, the main fields of innovation to date have been fuel-efficiency measures and automotive emission control technologies. Automotive fuel, such as petrol or diesel blends, consists of a mixture of saturated hydrocarbons (alkanes, such as heptanes, iso-octane, cyclohexane) and a smaller amount of unsaturated hydrocarbons [alkenes (olefins), alkynes (acetylene), and arenes (or aromatics, such as benzene or toluene)]. It is manufactured by fractional distillation of crude oil (yields about 25% of petrol from a unit of crude oil), which may be complemented with cracking and isomerisation (which allows to double the yield of hydrocarbons in the petrol range). A number of chemical compounds are added to motor fuels to improve performance or to meet various environmental standards.
- 25. To provide some background for understanding several inventions related to petroleum-based traditional cars, consider the standard combustion technique. In a traditional combustion process, the relative weight of air to fuel in the combustion mixture has important implications for engine power, fuel consumption (CO₂ emissions), as well as pollutant concentration in the exhaust gases leaving the combustion chamber. The relationships are complex, as is suggested by Figure 2 below. It suggests that maximum power is obtained for a slightly rich mixture, while maximum fuel economy occurs with slightly lean mixture (*i.e.* more air than the stoichiometric ratio). During the period before emissions regulations were introduced, cars were thus designed to run on slightly rich mixtures for better power and performance (Masters and Ela, 2008).
- 26. However, a rich air-fuel mixture leads to production of relatively large amounts of CO and unburned HC emissions, since there is not enough oxygen for complete combustion. A lean mixture (more air than necessary) helps reduce CO and HC emissions unless the mixture becomes so lean that misfiring

Although one is likely to also expect regulatory standards and fuel taxation on vehicles to trigger invention in alternative devices, such as cars driven on hydrogen or electricity, we leave this for future work.

occurs. Hence, after the first regulations of CO and HC emissions were introduced in the 1960s in the U.S., the initial response of manufacturers was to redesign cars to run on a less rich mixture (introduction of air-to-fuel ratio devices).

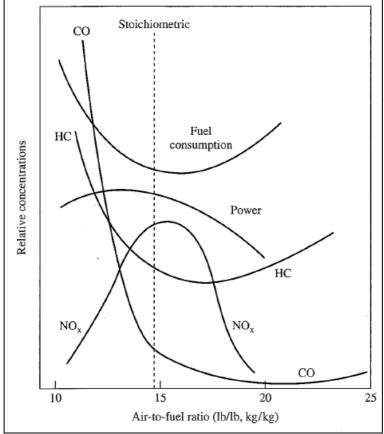


Figure 2. Effect of air-fuel ratio on emissions, power, and fuel economy (petrol engines)

Source: Masters and Ela (2008), pp. 408.

- 27. Production of NO_x is primarily driven by the combustion temperature; it is affected by the airfuel ratio only indirectly, in a bell-shaped manner (Figure 2). While for rich mixtures, the lack of oxygen lowers combustion temperature thus reducing NO_x emissions for lean mixtures, more oxygen increases combustion temperature, hence increasing NO_x emissions. However, beyond a certain point, lean mixtures may have so much excess air that the dilution lowers flame temperatures, and lowers NO_x production. Therefore, when also NO_x became regulated (through the 1970 Clean Air Act in the United States), modifying the air-fuel ratio was no longer sufficient, and manufacturers had to turn to the 3-way catalytic converter (Masters and Ela, 2008).
- 28. Introduction of the three-way catalytic converter required the development of precise electronic feedback control systems (like On-Board Diagnostic systems) that monitor the composition of exhaust gases and feed that information to a microprocessor-controlled carburettor or fuel-injection system (Masters and Ela, 2008). Development of such 'closed-loop' systems with a high degree of control was necessary for the three-way catalytic converters to operate effectively. This is because they must operate within a very narrow band of air-fuel ratios, near the stoichiometric value (see Figure 3). In diesel engines, electronically controlled fuel-injection (such as common rail and unit injectors) was introduced in order to allow flexible injection timing, rate shaping, and higher injection pressures.

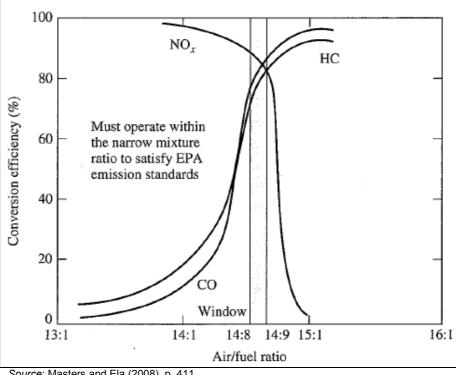


Figure 3. Effect of air-fuel ratio on conversion efficiency of catalytic converters

Source: Masters and Ela (2008), p. 411.

Other ways to reduce emissions is to improve the combustion engine process. In particular, technologies have been introduced to improve the droplet formation in hot spots, i.e. local confluence of fuel. For instance, technologies that reduce the hot spots by better fuel distribution were developed in the 1990s. Also technologies that increase the temperature of exhaust gases improve burning conditions which, in turn, is useful in reducing emissions.

3.2 Patent database

For this study, we have used the new EPO/OECD World Patent Statistical Database or PATSTAT for short. Over the last several years, the OECD's Directorate for Science, Technology and Industry, jointly with other members of the OECD Patent Statistics Taskforce, 12 have developed a patent database that is suitable for statistical analysis - the OECD Patent Statistics Database. Recently, further work has been undertaken by the Taskforce members towards developing this worldwide PATSTAT patent database. The European Patent Office (EPO) took over responsibility for development and management of the database, which is now drawn directly from the EPO's master database (Rollinson and Lingua, 2007).

The PATSTAT database has been developed specifically for use by governmental and intergovernmental organisations and academic institutions and is optimised for use in the statistical analysis of patent data. It has become a primary source of patent data information for statisticians, academics, and policy advisors (Rollinson and Heijnar, 2006). The PATSTAT database has a worldwide coverage (80 patent offices) over a time period stretching back to 1880, and contains over 70 million patent

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Other Taskforce members include the European Patent Office (EPO), Japan Patent Office (JPO), United States Patent and Trademark Office (USPTO), World Intellectual Property Organisation (WIPO), National Science Foundation (NSF), Eurostat, and DG Research.

documents.¹³ It is updated on a regular basis, every 6 months. Patent documents are categorised, using the international patent classification (IPC), European classification (ECLA),¹⁴ and national classification systems. In addition to the basic bibliometric and legal data, the database also includes patent descriptions (abstracts), standardised applicant and inventor names, as well as harmonized citation data. The *PATSTAT* database is thus an ideal source of patent data information for the purposes of this study.¹⁵

- 32. The final counts were generated as the number of "claimed priorities", which are patent applications that have subsequently been claimed as priority elsewhere in the world. The applications are disaggregated by priority year (based on the first filing-date worldwide), inventor country (country of residence of the inventors, using fractional counts), and technological field (based on IPC classes). The use of fractional counts accounts for potential multiple inventors for one application. So, if different inventors are involved in one application, *e.g.* from Germany, US and Belgium, than this application adds only 1/3 to the mentioned inventor countries.
- 33. The patent counts obtained this way have several advantages. First, considering only priority applications (and not their duplicates), we avoid double-counting which would occur if data from multiple patent offices were pooled. The data is thus better suited for cross-country analysis. Second, considering only 'claimed' priorities provides a 'quality' threshold as priority applications which have never been claimed are excluded. This helps contain any concerns over strategic patenting. Third, the data are truly worldwide in their coverage, as the entire stock of patent priorities is considered. It follows that patent counts are attributed geographically solely through inventors' country, independent of the priority filing office.

3.3 Patent selection

34. We are interested in *counting* and therefore identifying patents that can be linked to the substitution channels mentioned in Section 2.1. ¹⁶ Therefore, we categorize our patent records in four categories (see also Table 1 and Appendix A). The first group consists of end-of-pipe *emission abatement* techniques, also called post-combustion (after-treatment) devices. Post-combustion controls include end-of-pipe measures that capture and/or treat emissions after they have been formed and are therefore called 'secondary'. Such technologies often require complementary measures which must be integrated with engine design, such as sensors and fuel injection. A second group of patents is related to the *characteristics* of the fuels and the additives used to enhance productivity and emission intensity of the combustion process. Third, we consider a set of technologies that involve *engine redesign*, *e.g.* through the introduction of combustion technologies that typically improve the combustion process itself in order to reduce the forming of emissions. For this reason they are called primary measures. Finally, we include counts of typical technologies that improve *fuel efficiency* through alternative design of cars, like their aerodynamics, or other characteristics, such as rolling resistance. Table 1 provides an overview of the patent categories we

¹³

This includes patent documents from the EPO, USPTO, JPO, and other national and regional patent offices, as well as international patent applications filed under the Patent Co-operation Treaty (PCT).

The ECLA classification system is an extension of the IPC and contains 132 200 subdivisions, *i.e.* about 62 000 more than the IPC.

Due to differences in *PATSTAT* with respect to the availability of English language abstracts, it has not been possible to develop counts based on keyword searches of abstracts. Efforts to impute the relevant counts based upon the data available did not provide credible counts. Consequently, only IPC classes where no keyword searches were necessary are included in the final search strategy.

Recent work from de Vries (2007) and Crabb and Johnson (2007) are used to assess to what extent these channels can be made operational for the field of automotive-generated emissions. See Appendix A for further explanation.

have selected and their impact on the reduction of some important pollutants as well as on fuel consumption.

Table 1. Fuel Efficiency and Emission Control Technologies for Automobiles

			Effect o	n Main poll	utants ²⁾	Effect on
	Code	Focus ¹⁾	NO _x	нс	со	fuel cons ²⁾
Emissions (post-combustion)						
Catalytic converters	CAT	S	ı	_	_	+
Devices for fuel heating, reforming	FHR	S	ı	_	_	+
Crankcase	CRK	S		_		
Thermal reactor	THR	S		_	_	
Input (fuel characteristics)						
Oxygen containing additives and Anti knock additives	OKA AKA	Р		_	_	0
Input (improved engine (re)design)						
Air-fuel ratio devices	AFR	P/S	-	_	_	_
Sensors	SRS	P/S				
Fuel injection	FIN	Р	_	_	_	_
Exhaust gas recirculation	EGR	Р	ı	_	_	0
On Board Diagnostic systems	OBD	Р	_	_	_	_
Ignition timing	IGT	Р	ı			+
Output (fuel efficiency)						
Air resistance (aerodynamic design)	ARS					_
Rolling resistance	RRS					_
Other fuel-efficiency support systems	FSS					_

¹⁾ S=Secondary (after emissions are being formed) and P= Primary (prevent forming of emissions)

4. Environmental and tax policy description

4.1 Standards

- 35. This section describes motor vehicle regulation in the major OECD countries since the beginning of the 1970s, in particular for the US, Japan and the EU. Some countries within the EU may have implemented more strict regulations than the EU, but so far we have not found such data. Regulatory standards are mainly related to emissions by cars with one major exception, which is the CAFE standards used in the US since the end of the 1970s. Subsequently we shortly describe regulation of both petrol and diesel cars:
 - i. specific tailpipe standards on car exhausts, such as regulations for CO, HC and NO_x and PM
 - ii. motor fuel input requirements, such as regulations on the lead or sulphur content of the fuels;
 - iii. fuel-efficiency standards for motor vehicles.

Tailpipe standards

36. With respect to tailpipe standards, the OECD Environment Department has already compiled a very detailed database that describes the 'command and control' regulation of automotive emissions for both gasoline and diesel cars in the EU, Japan and the US (see Hascic, 2006 and de Vries, 2007). We summarize these findings in separate graphs for CO regulation for both diesel and gasoline cars, as well as

²⁾ A minus implies a reduction of emissions or an improvement of fuel efficiency

for HC and NO_x for both type of cars separately, and, finally, regulation of PM (see Figures 4-7).¹⁷ Note that international comparisons of standards are notably far from straightforward because, for instance, test cycles may differ between countries (OECD/IEA, 1984; An and Sauer, 2004; Timilsina and Dulal, 2009). Therefore, our comparisons do *not* aim to shed light on the exact relative difference of these standards, but just to show when regulators decided to further tighten their restrictions.

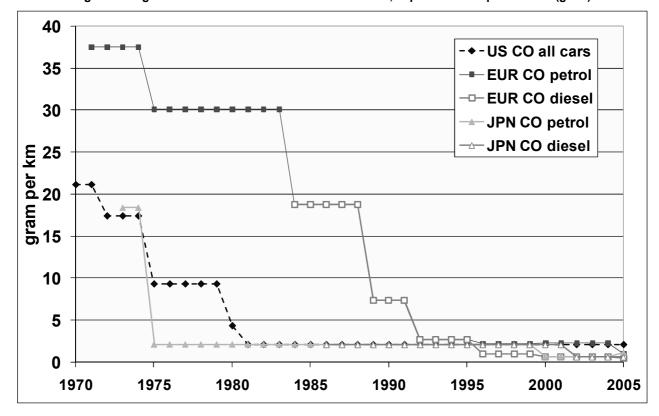


Figure 4. Regulation of CO emissions for cars in the US, Japan and European Union (g/km)

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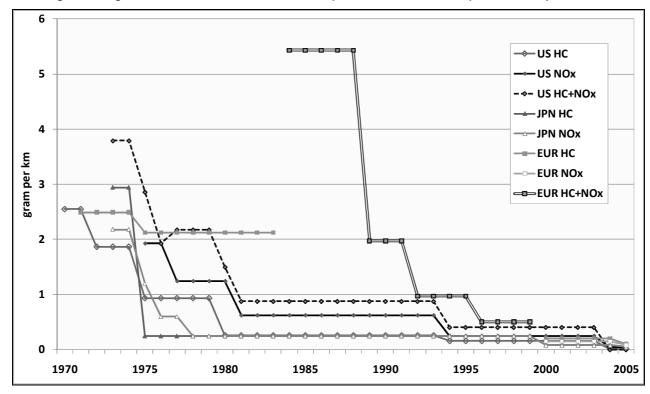
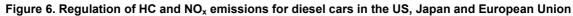


Figure 5. Regulation of HC and NO_x emissions for petrol cars in the US, Japan and European Union



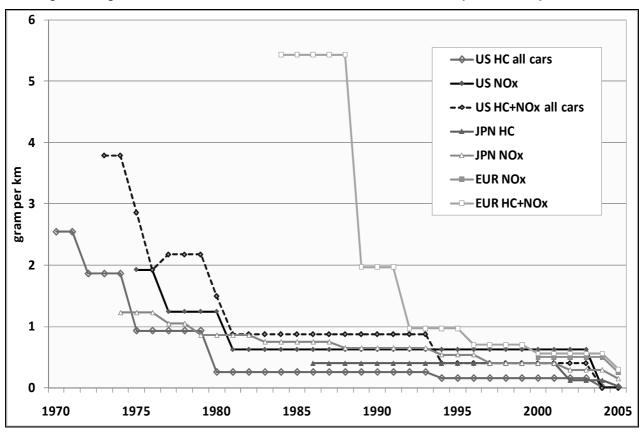




Figure 7. Regulation of Particulate Matter (PM) in the US, Japan and European Union

- 37. The picture that emerges for specific tailpipe standards on car exhausts, in particular regulation for CO, HC and NO_x and PM, boils down to the following observations:
 - i. US regulations were introduced rather early. Restrictions imposed under the Clean Air Act (CAA) became much more stringent in the 1970s for both petrol- and diesel-driven cars, but remained rather generous since this initial initiative. Overall restrictions have always been much more lenient than in Japan with the exception of regulation for HC;
 - ii. *Japan* introduced regulations for CO, HC and NO_x somewhat later than the *US*, but these regulations have always been particularly strict for from the very beginning. Only regulation for diesel cars has always been more lenient, probably because the share of diesel cars was also very small throughout our sample period;
 - iii. European Union was typically late and rather lenient for most exhaust gases from the very beginning probably due to its limited regulatory power in those days. Since the introduction of the Euro I standard in 1992, the standard-setting process in the EU rapidly caught-up with, and subsequently sometimes even appears to outrun, the stringency of regulations in the US under Euro III. Although care should be taken in such comparisons based on absolute standards, the differences in level seems to have become much smaller over time and Japan's regulations tend to remain the strictest for the three exhausts considered (see also An and Sauer, 2004).
 - iv. The difference in regulation between petrol- and diesel-driven cars can be substantial, particularly in the *EU*, where diesel cars obtained a substantial market share rather early. CO standards became even stricter for diesel cars compared to petrol cars since 1996. In the US,

- where diesel cars make up only a small share of the passenger car park, no such differences exist for CO and also Japan has similar standards. As to the regulation of HC and NO_x , substantial differences can be observed, however. In particular in the EU and Japan, standards have always been considerably more stringent for petrol-driven cars for both HC and NO_x .
- v. Regulation of Particulate Matter (PM) is of rather recent date. Here regulation started only in 1990 with the EU leading. Indeed, the share of diesel driven cars rapidly increased in the 1980s, particularly in Germany with its relatively (compared to petrol) low diesel tax. When in Japan the share of diesel gradually increased as well, regulations were also tightened. The EU typically took the lead with their Euro I-III standards in the 1990s. Since 2000, further restrictions could be observed in all areas.

Fuel quality regulations

- 38. Regulation of fuel quality is mainly related to the quality of the combustion technology on the one hand and emissions of CO, HCs, NO_x and PM on the other. In particular, anti-knock additives have been used to improve detonation resistance of fuel (petrol) blends. The original motivation was to improve the combustion potential of fuel (and thus increase engine power and durability). In the past, various lead-containing additives (*e.g.*, tetraethyl lead) were used, because this was the most cost-effective way of boosting the octane levels (see *e.g.*, Kerr and Newell, 2003). However, environmental and health considerations of lead-related air pollutants as well as the incompatibility of lead with the use of catalytic converters spurred the search for alternatives.
- As a result, lead (Pb) standards were introduced, hence creating a gradual phase-out of leaded petrol in the US during the 1970s and 1980s (*e.g.*, Kerr and Newell, 2003). The phase-out of lead in Japan one of the first OECD countries to reduce the amount of lead in gasoline also took place gradually. Japan started its phase-out during the 1970s; by the early 1980s, only 1-2% of petrol contained lead (Michaelowa, 1997). The production and use of leaded petrol has now been fully eliminated in Japan. Finally, in Europe, Germany was the first country to adopt standards to control the lead content of petrol ranging from 0.4 grams lead per litre in 1972 (benchmark of 0.6 grams per litre) to 0.15 grams of lead per litre in 1976. In addition, in 1985, Germany passed a law to reduce total automobile emissions, and included the introduction of unleaded petrol, because the largest reductions of NO_x and CO could be achieved by catalytic converters that were incompatible with lead (Von Storch *et al.*). As of 1981, the EU set a standard of 0.4 grams lead per litre (Council Directive 78/611/EEC), which lagged almost a decade behind the German law. As of October 1989, all EU Member States had to offer unleaded petrol, with a

In the United States, the lead phase-out began by requiring that new cars after 1974 use unleaded petrol, and ended with an eventual ban in 1996 (Kerr and Newell 2003).

Anti-knock (anti-detonation) agents are added to increase the octane rating of petrol and thus improve the smoothness of the burning process. In internal combustion engines, the compressed petrol-air mixtures have a tendency to ignite prematurely, rather than burning smoothly. Hence, a fuel with higher octane ranking allows higher compression ratio, without causing premature detonation (knock). While low autoignition resistance is problematic in spark-ignition engines, it is desirable in diesel engines. Resistance of petrol to auto-ignite or detonate when compressed is measured by the octane number. The tendency of diesel fuels to auto-ignite is measured by the cetane number.

Isomerisation allows producing high-octane blending components (isomers) and hence represents an alternative approach to adding fuel additives. Isomerisation is a process of altering hydrocarbon molecules to produce compounds (*e.g.*, isopentane, isohexane) which have higher octane rating; it does not involve adding or removing any substances (see *e.g.*, Pellegrino 2007). For example, the switch from leaded to unleaded petrol in the United States was, to a large degree, possible due to the commercialisation of pentane-hexane isomerisation technology which allowed boosting octane levels without using lead additives (Kerr and Newell, 2003).

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maximum of 0.15 grams of lead per litre. The 1998 Aarhus Treaty required the use of only unleaded petrol by 2005.

Policies aimed directly at improving fuel efficiency

- 40. Direct regulation of fuel efficiency aims o lower the amount of fuel required to move a vehicle over a certain distance, for example in Miles per Gallon (MPG) or litres per 100 kilometre (L/100km) driven. Accordingly, fuel efficiency is increased if MPG becomes higher or L/100km is lowered. Such standards typically apply to the average of a fleet of cars with specified weights.
- 41. Interestingly, mandatory fuel efficiency requirements is exceptional across the world. In fact, the only example is the application of the Corporate Average Fuel Economy (CAFE) standards in the US introduced in 1978. After an initial increase in stringency, the gradual tightening was shortly relaxed after 1984 when it really had byte. Since 1989, however, the standard has never been changed (An and Sauer, 2004). In contrast, voluntary schemes have been applied much more often. In particular around the oil crises of the 1970s several of such agreements were in force in OECD countries like Germany and Japan (OECD, 1984). And also recently several countries negotiated with car manufacturers and importers to further improve fuel efficiency in order to reduce car related greenhouse gases like CO2 (ECMT, 2007).
- 42. Figure 8 summarizes our findings. The CAFÉ standards were increased dramatically between 1978 and 1984 and were then temporarily relaxed and have remained at the same level since 1989. These levels also are typically more lenient compared to other regulators, *e.g.* in Japan and Germany. For instance, Japanese voluntary agreements, agreed upon around 1980, was to reduce fuel use 12.3% from 8.8 litre per 100 km in 1978 to 7.8 litre per 100 km in 1985 (on average; weight based differences), and also in Germany the target was to reduce fuel use 12 to 15% in 1985 compared to the level of 1978. Also other countries had comparable agreements, like Australia and Canada (more closely to US) and Italy and Sweden (more closely to German standards). Only recently EU took the lead and introduced the strictest (average) standards.²¹

However, Japanese standards are specified somewhat differently. For a comparison of the strictness of the early standards see OECD/IEA (1984).

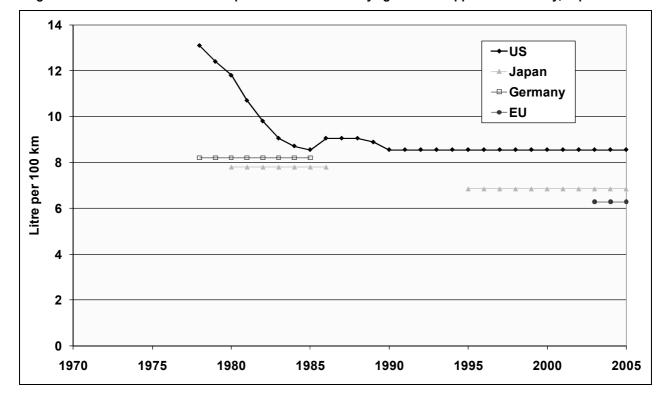


Figure 8. CAFE standards in US and periods where voluntary agreements applied in Germany, Japan and EU

4.2 Fuel taxes

43. Like net-of-tax petrol and diesel prices, one might expect petrol and diesel excises to have an impact on technological change. Moreover, governments can use these excises not only for revenue raising purposes, but also for internalizing externalities (Newbery, 2005) and even if not by purpose, they are always implicit regulatory taxes. The use of excise taxes on motor fuels as an efficient instrument of environmental policy is far from straightforward. Taxes on fuels are only *indirect* emission taxes and the dynamic incentives they represent very much depend on the choice of excise base and rate.²² Whatever their purpose, even if excises are implemented for revenue raising purposes, they still act as implicit regulatory devices because they increase the (relative) level of price by the amount of tax. Apart from motor fuel taxes, typically also car ownership taxes as well as special purchase taxes may be applied.²³

44. This is not the place to discuss environmental tax policy initiatives on motor vehicles throughout the OECD in the past 40 years (OECD, 2007). Instead we focus on the potential effect of motor *fuel taxation*, because these taxes can be targeted by car-making firms in response. Indeed, car ownership taxes cannot directly be affected by mutability of cars although the relative penetration of types does matter for the relative importance of R&D investments in either diesel or petrol cars. Note, furthermore, that technological change is also likely to be only indirectly affected by tax differentials based on motor fuel

Also interaction with other externalities from transport, including congestion, is important. See Fullerton and West (2002), Newbery (2005) and Parry and Small (2005) for examples of comprehensive theoretical evaluations of taxes on motoring, including (energy) taxes on motor fuels.

For instance, the Netherlands used to tax the purchase of diesel-driven cars at a much higher level than petrol-driven cars which – in combination with fine-tuning of fuel taxes – has been used to prevent penetration of diesel cars in the Dutch car park. This policy has been remarkably successful even though it usually goes without notice (see Vollebergh, 2007).

characteristics because these taxes first of all have an impact on the penetration of fuels, not R&D activity to change combustion processes or search for alternatives.

45. Figures 8-10 present developments in fuel taxes on three major motor fuels in several representative countries in our data set. Data on excise rates are obtained from the OECD/IEA Energy Prices and Taxes Country Notes. This data contain information of the excise per litre of motor fuel for the period 1978-2005 in local currencies for most 'traditional' OECD-member states including the US and Japan. Because excises are unit taxes rather than *ad valorem* taxes, we also need to transform excise rates into a common unit of measurement. We do so by using annual exchange rates of local currencies and consumer price index (CPI) to convert the data into real USD values.²⁴

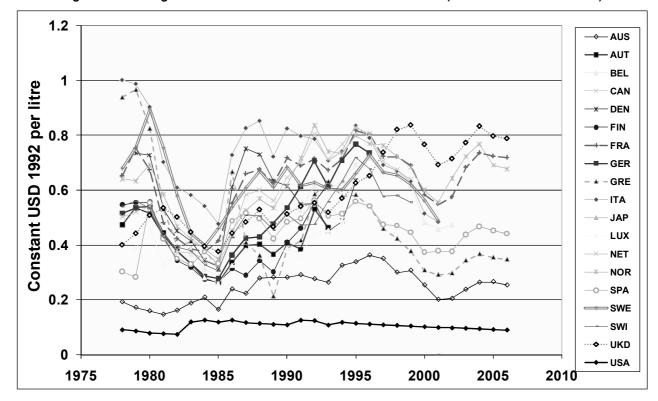


Figure 9. Leaded gasoline excises in 19 OECD countries 1978-2005 (in constant USD 1992/litre)

46. The first two figures summarize the most important excises for motor fuels, *i.e.* for leaded and unleaded petrol. Clearly remarkable differences exist between the countries in our sample over the whole period. Due to harmonization efforts and the implementation of minimum excise rates within the European Union, levels within the EU gradually began to develop within a narrower band. Originally the purpose of the EU was to introduce a harmonized excise rate at pre-specified levels for motor fuels (see first Directive on Mineral Oil Excise Harmonization in 1987 [COM(87)]). This policy has never been applied in practice, however, and settled at minimum rates applied in 1992. This minimum rate remained unchanged between 1992 and 2004. Interestingly, no excise rate is applied to leaded petrol in Japan because this fuel is not on the market. Even more remarkable is that the development of the excise rate applied in Germany relative to the US converged in the 1970s and next gradually increased with a sharp turning point in 1985. Fewer observations exist after 1995, as more and more countries banned leaded petrol from the market. Now looking at a similar picture for unleaded petrol (Figure 9), we observe a similar pattern for the US and

One should keep in mind that this means that exchange rate fluctuations also cause fluctuations in the excise rates, even when countries do not change their excise rates.

Germany. Since 1985, excise rates strongly went up in Germany, then more or less moved in step with the US until 2000, and then again sharply diverge. The pattern for the Japanese excise more or less follows the pattern of Germany, although with several exceptions.

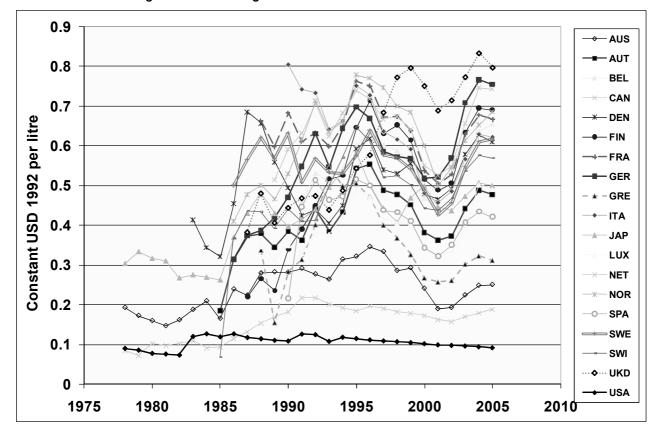


Figure 10. Unleaded gasoline excise in 19 OECD countries 1978-2005

47. Finally we present the development of diesel excises over time (Figure 10). Again, remarkable differences exist between the countries in our sample, in particular between the US, Japan and Germany. At face value, variation appears quite similar in our sample period, in particular because (real) excise rates in the US were more or less constant over time. There seems to be some convergence for EU member states, due to harmonization efforts and the implementation of a minimum diesel excise rate within the European Union. Both Japan and the US had relatively low levels until 1985, whereas Germany rapidly lowered their rates to almost similar levels in this year. Since then, Germany increased levels gradually over time, in particularly after 2000. Again, Japan more or less followed this pattern though at considerable lower levels, whereas the US has almost constant levels throughout our sample period.

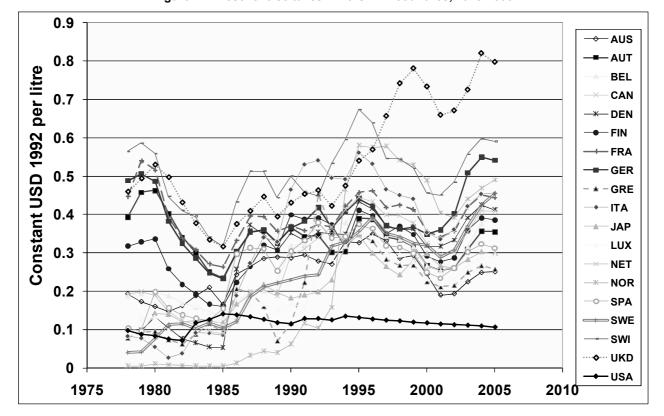


Figure 11. Diesel excise taxes in 19 OECD countries, 1978-2005

5. Descriptive Analysis

could shed more light on this issue.

48. This section describes the patent data for our sample countries which cover a sufficiently long time horizon to allow for proper identification of the differential impact on patents of specific fuel taxation relative to standards, and net of tax price variation. Our original patent data count is a panel data set for 31 countries between 1980 and 2005 (See Appendix C). This sample includes major previous and current car-producing countries, like in particular the USA, Japan and Germany, but also the UK, France, Italy, Spain, Sweden, the Czech Republic and Korea. Interestingly, the number of counts outside the traditional car-producing countries is only 729, or 1% compared to the overall number of 60,556 counts. This implies that innovative activity was very low outside the traditional car-producing countries before 2005, and we restrict our subsequent analysis to these countries accordingly.

49. Table 2 presents the distribution of all patent counts across the 19 OECD countries and 14 technologies mentioned before. Like in other areas of environmental innovation, again the most important countries are Japan, Germany and the U.S. Together these countries account for roughly 89% of the overall number of patents, with Japan filing by far the largest number of patents with its contribution of almost half of the overall number of counts (47.2%), followed by Germany (28.3%) and the U.S.

Car-producing companies may react to regulations in other countries, in particular if they provide important sales markets to them. However, the propensity to patent will depend in large part upon the nature of the innovation and supply chains. For instance, some innovations will be embedded in car exports, obviated the need to patent. A more extensive patent search across a larger subset of countries

Both the distribution across countries as well as technologies is almost exactly equal for the sample of 31 and 19 countries.

(13.7%).²⁷ For the other countries, France stands out most, producing 4.3% of the total number of patents. The second major observation is that innovation on electronic control systems (OBD) is most prominent (32.7%), followed by innovation on fuel injection systems (FIN) (18.8%) and catalytic converters (CAT) (17.2%). The joint contribution of these three fields in total innovation is about 68%.

50. The evolution of the number of patent applications in the major patenting countries, in particular Japan, U.S., Germany, France and Italy, for the period 1965-2005 is shown in Figure 12. Hardly any innovative activity is present in the first part of the period. Apart from a spike around 1975 in Japan, patenting activity increases steadily since the early 1970s. After an initial rise of patenting activity in the 1970s, there is more or less stabilisation until 1995 when another 5-year during take-off period can be observed, in particular in Germany. Figure 12 also shows that overall patenting in the area under study in both Germany and the U.S. decreases somewhat earlier compared to Japan, whereas the growth of France's patenting at the end of our sample period is remarkable, and even larger than that of the U.S. Overall, patent activity has grown steadily in these countries until almost the end of the sample period, and this trend is particularly prominent and early for Japan and Germany, with France picking up at the end of the period.

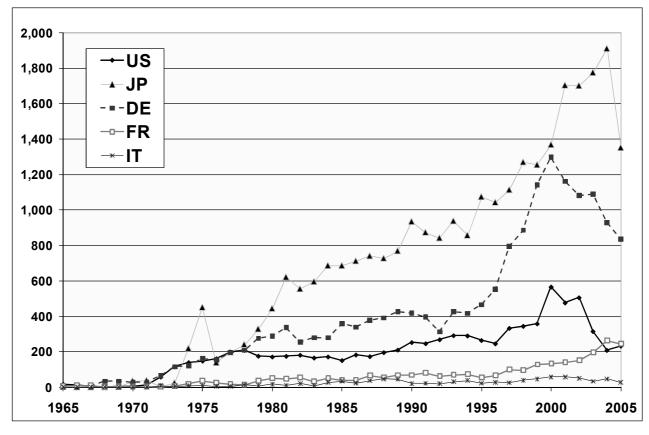


Figure 12. Evolution of patent applications in main inventing countries, 1965-2005

Note that until the late 1980s, each Japanese application could only include one claim. For instance, a patent with 3 claims in the U.S. would imply three separate patents in Japan. Even today, Japanese patents tend to have fewer claims.

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Table 2. Patent counts for major motor vehicle emission control and fuel efficiency measures in 19 OECD countries 1965-2005

		Emissi	ons		Input (fuel)	Input (engine)					Output	(fuel effi	ciency)	Total		
Country	CAT	FHR	CRK	THR	OCA/AKA	AFR	SRS	FIN	EGR	OBD	IGT	ARS	RRS	FSS	#	%
US	1677.1	381.3	74.6	28.0	18.7	786.6	166.2	1613.8	466.2	1928.9	352.6	100.8	375.3	226.8	8196.9	13.7
JP	4511.1	426.5	167.7	60.2	11.0	2582.7	321.8	3414.1	1583.7	11606.5	1908.3	88.0	510.9	1019.9	28212.5	47.2
DE	2796.1	343.3	170.6	51.5	8.0	1019.4	406.7	4856.9	752.3	4706.3	518.0	155.2	453.4	689.7	16927.5	28.3
AT	38.5	11.0	2.4	0.5	0.0	39.3	9.2	227.8	29.6	95.3	4.9	8.2	9.5	6.9	483.1	8.0
AU	2.2	3.0	0.0	0.0	0.0	13.7	0.0	15.4	1.0	12.5	3.0	2.0	4.0	1.5	58.3	0.1
BE	24.4	0.2	0.0	0.0	0.0	10.0	1.8	6.1	3.8	12.8	0.2	2.0	2.5	1.3	65.1	0.1
CA	51.5	24.6	2.0	0.0	0.2	107.8	5.0	41.5	46.5	35.2	8.7	16.0	21.1	7.0	367.1	0.6
CH	38.6	8.7	0.5	2.0	0.0	25.7	2.6	65.6	9.5	26.0	1.0	0.3	10.8	0.7	192.0	0.3
DK	21.2	4.5	0.0	0.0	1.0	12.8	0.0	48.6	11.0	11.0	2.0	2.0	3.0	1.0	118.1	0.2
ES	9.6	12.2	0.0	1.0	0.0	22.5	0.0	18.8	8.6	9.8	0.1	2.0	10.1	2.0	96.7	0.2
FI	59.3	6.0	1.0	2.0	0.0	21.5	0.8	37.9	10.0	6.1	0.0	2.0	7.0	2.0	155.6	0.3
FR	608.6	93.4	10.0	5.0	2.2	204.4	83.5	391.5	181.0	570.9	86.0	36.1	226.1	51.8	2550.6	4.3
GB	126.3	32.2	11.0	1.3	0.0	84.9	6.8	119.8	61.9	132.4	25.6	12.0	21.2	22.7	658.2	1.1
GR	3.5	4.0	0.0	0.0	0.0	7.9	0.0	0.3	3.0	2.3	0.0	0.0	5.0	0.0	26.1	0.0
IT	116.9	36.9	9.0	5.0	1.9	50.7	10.2	274.5	29.8	208.6	37.7	19.0	46.4	20.2	866.8	1.4
LU	4.8	1.0	0.0	0.0	0.0	3.3	2.0	8.4	3.0	17.4	1.5	0.0	2.7	1.0	45.1	0.1
NL	46.3	10.0	0.0	0.5	0.0	8.9	5.2	25.3	3.7	16.4	2.0	0.0	5.1	3.7	127.1	0.2
NO	6.0	2.0	0.0	0.0	0.0	4.0	0.0	2.7	1.0	1.0	0.0	0.0	5.0	1.0	22.7	0.0
SE	121.1	19.7	22.0	2.6	0.0	91.6	12.0	55.3	82.2	166.8	21.0	14.3	8.0	40.3	657.0	1.1
Total	10263.1	1420.5	470.8	159.6	43	5097.7	1033.8	11224.3	3287.8	19566	2972.6	459.9	1727.1	2099.5	59826.5	100
%	17.2	2.4	0.8	0.3	0.1	8.5	1.7	18.8	5.5	32.7	5	0.8	2.9	3.5	100	

51. Using our categorization of technologies (see Table 1), Figure 13 shows that most innovation occurred in the field of input combustion (72%), where on-board diagnostic systems (OBD) and fuel injection (FIN) related patenting are the most important subcategories, contributing 32.7% and 18.8% respectively. Furthermore, about 21% of patenting is concentrated on emissions- or tailpipe-related technologies, where the main subfields are catalysts (CAT) (17.2%). Innovation on output-oriented technologies, such as aerodynamics and rolling resistance (ARS, RRS and FSS), appears to be a minor subfield, contributing about 7% of the overall counts. Hardly any innovation has occurred in the field of fuel input characteristics (0.07%).

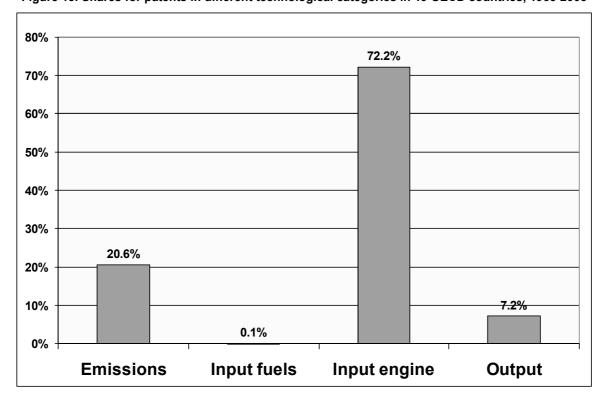


Figure 13. Shares for patents in different technological categories in 19 OECD countries, 1965-2005

52. In order to describe *when* innovation in *which* technological category occurred, Figure 14 plots the number of patent applications of each group for the period 1965-2005. In particular, the largest technological subfield, input combustion, shows an upsurge both in the 1970s and again between 1995 and 2000, as well as a sharp relative decline since 2002. Patenting of tailpipe technologies ('emissions') shows a remarkable steady increase over time, with only a sharp increase in the years preceding 1975 and 1998. To a great extent, the evolution of patenting in the domain of emissions-related technologies is similar to the pattern for input combustion, however, always at a considerably lower absolute level of patent applications.²⁸ Patents for technologies that directly reduce fuel consumption through an improvement in aerodynamics or rolling resistance tend to increase steadily in the 1980s, with a clear peak in 1986-1988, and reveal again a sharp boost in the years before 2002. Then, as with the other technological domains, the degree of patenting goes down again. Finally, for patenting related to input fuel technologies, hardly anything seems to be going on for the whole period 1965-2005. With only 43 applications filed, this is hardly surprising.

Note that because of scaling (due to input combustion patent numbers), Figure 14 does not clearly reveal the patenting activity in the fields of emissions- and output-related- technologies.

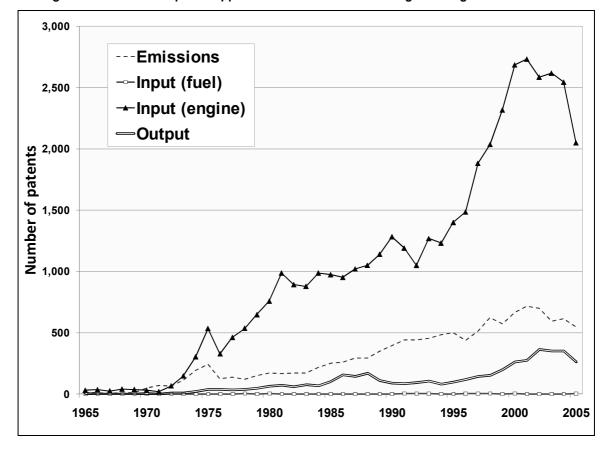


Figure 14. Evolution of patent applications for the four technological categories in 1965-2005

6. Econometric analysis

6.1 Introduction

Clearly our database is very rich in detail. The data not only cover patent data on several different technologies, but also a large spectrum of relevant regulatory interventions in many countries during a long period. As a first step to further explore this dataset in the future, this section presents results of a preliminary analysis focusing on the three main inventing countries, Germany, Japan and the USA. Several reasons justify this initial focus. First of all, almost 90% of all patented inventions in car technology are located in these three countries. Even though, for instance, Canada has large car assemblage factories, many of the engineers are located in Detroit, not in Canada. Similar patterns can be observed for Germany and Japan. Second, limiting the analysis to only three representative countries facilitates the creation of a full panel for all regulatory variables which already requires a lot of effort. Finally, for these countries we observe positive fractional numbers for most (aggregated) technology groups, which justifies (initial) econometric simplifications. In this section we, first of all, present our estimation model and summary statistics, and next we present some initial results.

6.2 The model

54. We construct an empirical model of the effect of public policy (standards, taxes) and other determinants on inventive activity in our main automotive technology classes. The model takes the following form:

(1)
$$ENVPAT_{i,t} = \beta_1 STD_X_{i,t} + \beta_2 STD_F E_{i,t} + \beta_3 PRICE_{i,t} + \beta_4 TAX_{i,t} + \beta_5 R \& D_{i,t} + \beta_6 TOTPAT_{i,t} + \alpha_i + \gamma_t + \varepsilon_{i,t}$$

where i indexes country and t indexes year. The dependent variable is measured by the number of patent applications in the different automotive technology categories and we estimate equation (1) for each category separately. As noted before, our patent counts only include high-value patents (claimed priorities, deposited worldwide).

- 55. The key explanatory variables include emission standards (STD_X_t) , fuel efficiency standards (STD_FE_{it}) , fuel (petrol) prices $(PRICE_{i,t})$ and fuel excises $(TAX_{i,t})$. All of the policy measures vary across countries and over time. Note that the focus of (1) is on *contemporaneous* effects of the regulations and we leave time-related estimations for future work.²⁹ Our major control variable is total patents, to control for the variation in a country's general propensity to invent and patent technologies over time $(TOTPAT_{i,t})$. In addition, country fixed effects (α_i) and, for some models, year fixed effects (γ_t) are included. All the remaining variation is captured by the error term $(\varepsilon_{i,t})$.
- 56. As a first step in exploring our data set, we exploit our main categorization of the (aggregated) technology groups as our dependent variables, *i.e.* emission abatement (*EM_CONTROL*), engine (re-) design technologies (*INPUT_ED*) and fuel efficiency measures that are unrelated to engine design (*OUTPUT_FE*). This section presents results of a first preliminary analysis for these groups focusing on the three main inventing countries, Germany, Japan and the USA.³⁰ With this approach we can avoid the necessity of more complex estimation techniques (*e.g.* count data) because for the aggregated technology groups we have only few zero patent observations. Therefore we estimate (1) using Ordinary Least Squares (OLS).
- 57. Furthermore, the dynamics in the overall car market is likely to be determined by regulatory developments in these three countries, given the huge share in the home market for these firms in the first place. However, we also consider a model where the variable STD_FE_t represents the lowest efficiency standard in the three countries and hence only varies over time. We also test for this approach because in a non-autarkical trade regime, one country's fuel efficiency standard might have repercussions for inventive activity in other countries. Descriptive statistics for the estimation sample for Germany, Japan and the USA are reported in Table 3. Descriptive statistics for the estimation sample for Germany.

Both anticipated as well as lagged effects of regulation may have been important in determining inventive behaviour of firms. For instance, if firms anticipate more stringent future policies they are likely to increase their R&D effort in advance (see, for example, Dekker *et al.*, 2009).

We do not analyze patents for fuel input inventions given its very small number of counts.

On the contrary, assumption of autarky would imply that environmental standards only have an effect in their jurisdictions, with no effect on foreign inventors.

Note that correlation between standards is limited with the exception of the NO_x standard with the other emission standards and PM with HC. Therefore we also extensively tested for potential problems due to multicollinearity between these standards.

Variable	Units	Number	Mean	St. Dev	Min	Max
Emission	Count	108	98.75	81.65	0	359.34
Input Engine	Count	108	360.24	332.04	0	1408.7
Output	Count	108	33.49	34.07	0	159.83
Petrol Excise	Real prices	108	0.39	0.22	0.07	0.73
Petrol Price	Real prices	108	0.45	0.26	0.14	1.36
Standard CO	km/g ¹⁾	108	3.83	3.39	0	14.9
Standard HC	km/g ¹⁾	108	5.68	14.4	0	107.23
Standard NO _x	km/g ¹⁾	108	3.28	4.39	0	22.99
Standard PM	km/g ¹⁾	108	7.61	16.36	0	100
Fuel Efficiency Standards	litres per 100 km	108	4.36	4.26	6.28	13.1
Total Patents	count ('000)	108	18.66	10.89	0.04	48.9
1) A 0 means no regulation.						

Table 3. Descriptive Statistics

6.3 Empirical results

- 58. Our results sketch rather different pictures for each of the technology groups. The technologies that we ranked as *emission abatement* mainly correlate with the standards for CO and for fuel efficiency, but not with the other standards [see column (1) in Table 4]. The standards for CO and fuel efficiency have a statistically significant effect on inventive activity and also of the right sign.³³ This is hardly surprising for CO because these technologies reduce CO from car exhaust (see also Table 1). That fuel efficiency standards have an effect is probably that these inventions reduce emissions but also *decrease* fuel efficiency. Therefore, policies that aim to increase fuel efficiency are also likely to trigger further steps in optimizing this trade-off.
- As one might expect, petrol taxes have no contemporaneous effect on new inventions. However, we also find a strongly significant *negative* correlation between the gasoline price and new inventions. We find this negative correlation across all specifications for emission abatement technologies with the exception of adding time fixed effects [see column (3) in Table 4]. Adding time fixed effects to the standard model, however, *lowers* the explanatory power of equation (1) and we therefore accept model (1) as our base model. An explanation for the negative correlation is that rising (or falling) gasoline prices are unlikely to have a *contemporaneous* effect on inventions. Oil price spikes are usually unexpected and the first reaction by consumers is to reduce consumption of fuel by driving less and buying more fuel efficient cars from the existing stock of car models. This demand side reaction reduces already emissions on its own and therefore signals to inventors *less pressure* for inventing new technologies that control emissions! ³⁴ Finally, the propensity to patent is found to have a positive and significant effect also on patenting of these specific technologies.
- 60. These basic findings are robust to the exclusion of correlated standards such as the NO_x standard. However, we do not find any evidence for the hypothesis that inventors of emission abatement technologies are responsive to the strictest worldwide contemporaneous fuel efficiency standards [see column (2) in Table 4]. Although the other effects are hardly affected, the strongly significant negative effect of local regulation disappears. This suggests that inventors of new technology are mainly driven by

Note that the fuel efficiency standard is measured in litres of fuel per 100 kilometres driven. Hence the expected sign of this variable is negative.

Note that the implementation and/or a rise in excises is usually announced and debated (strongly) before it is actually implemented.

local policy measures, just as Popp (2006) has observed for SO₂ and NO_x abatement technologies for electric power plants.³⁵

Table 4. Empirical Results for Emission Abatement Technologies

	(1)	(2)	(3)
	9.30***	8.33***	9.54***
Standard CO	(2.84)	(2.94)	(2.75)
	-0.78	-0.70	-0.95
Standard HC	(0.61)	(0.63)	(0.71)
	1.60	2.70	-2.93
Standard NOx	(4.07)	(4.24)	(5.27)
	-0.38	-0.65	-0.13
Standard PM	(0.75)	(0.80)	(0.97)
	-3.00***		-0.52
Standard FE	(1.13)		(1.28)
		-0.09	
Standard FE (low)		(1.25)	
	5.67	39.42	-209.04***
Petrol Tax	(60.76)	(61.60)	(68.90)
	-67.01***	-96.46***	101.16***
Gasoline Price	(22.21)	(22.35)	(36.41)
	4.32***	3.90***	3.10***
Total patents	(0.56)	(0.59)	(0.90)
Country FE	YES	YES	YES
Time FE	NO	NO	YES
Adj R²	0.76	0.74	0.65
Number of obs	108	108	108
Groups	3	3	3

All estimations based on Ordinary Least Squares.

P-values in parentheses, based on robust standard errors. * p<0.05, ** p<0.01, *** p<0.001.

The results for the most important technology group in terms of counts, the *input technology* category, are quite different [see column (1) in Table 5]. Clearly CO has no effect on the overall number of patent counts for the underlying technologies, whereas especially NO_x reflects a strongly positive effect in this case. CO and NO_x standards appear to have a complementary effect on this type of inventions because CO becomes significant if we re-estimate this model without the somewhat problematic NO_x standard (see before). Somewhat surprisingly, however, are the results for both HC and PM. Both standards appear to reduce contemporaneous inventive activity because both coefficients are negatively significant. Looking more carefully in the original data of, in particular, Germany and Japan, it appears that this type of inventive activity peaked at the end of the 1990s, which is several years before further restrictions were introduced, in particular Euro IV in the EU. This also fits observations that particularly Euro IV regulations created much pressure on the automobile industry to find new ways to reduce the main pollutants from car exhausts jointly, particularly also for diesel cars. So this well explains why the

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Dekker *et al.* (2009) have shown recently that local inventors may strategically patent their new inventions in response to (expectations) of further increases in other countries' standards. Our current patent count does not allow for this type of analysis, however.

All other variables remain similar (results available on request).

standards for HC and PM appear to have had even a negative impact, because they were tightened before and particularly after the main inventive period.

Table 5. Empirical Results for Input (improved engine design) Technologies

	(1)	(2)	(3)
	-11.58	-15.60 *	-9.24
Standard CO	(8.96)		(7.41)
	-8.83 ***	(8.78) -8.13 ***	-8.36 ***
Standard HC	(1.91)	(1.88)	(1.91) 40.12 ***
	57.05 ***	62.90 ***	40.12 ***
Standard NOx	(12.83)	(12.63)	(14.12)
	-6.25 ***	-8.13 ***	-5.54 ***
Standard PM	(2.36)	(2.38)	(2.60)
	-4.49		0.59
Standard FE	(3.55)		(0.86)
		8.72 **	
Standard FE (low)		(3.72)	
	456.34 **	491.81 ***	-223.65
Petrol Tax	(191.37)	(191.37)	(185.62)
	-78.35	-196.32 ***	468.72 ***
Gasoline Price	(69.96)	(66.64)	(98.10)
	20.40***	18.37 ***	16.58 ***
Total patents	(1.77)	(1.76)	(1.76)
•	,		,
Country FE	YES	YES	YES
Time FE	NO	NO	YES
Adj R ²	0.90	0.90	0.89
Number of obs	108	108	108
Groups	3	3	3

All estimations based on OLS.

P-values in parentheses, based on robust standard errors. * p<0.05, ** p<0.01, *** p<0.001

- The strong positive effect of the petrol tax on engine redesign technologies is also remarkable. This effect is statistically even stronger if we re-estimate the model with the world lowest fuel efficiency standards [column (2) in Table 5] or without the (insignificant) standard for fuel efficiency (not included). However, this result fails to pass several robustness checks, including adding time fixed effects [see model (3) in Table 5]. Somewhat surprisingly, the signs of both tax and petrol price switch, whereas only the gasoline price remains significant if we allow for time fixed effects. Again this specification is robust to inor exclusion of different variables in specification (1) including petrol tax and price one by one (because of potential multicollinearity problems). For this reason we conclude that this result is not robust enough to state that increasing petrol taxes induces inventors of car engine technologies.
- 63. A final set of estimations looks at the main drivers of the *output technologies*, mainly fuel efficiency improvement technologies. One would typically expect fuel efficiency standards to be the most important driver here. However, these measures seem to have had no effect at all [see Table 6 column (1)]. Neither do we observe a positive contemporaneous effect by fuel market prices. What is the most important driver, however, are petrol taxes. The positive effect for taxes is confirmed by other specifications, including one with lowest fuel efficiency standard [model (2)], a model without NO_x standards which controls for potential multicollinearity with other standards [model (3)], but also adding time fixed effects does not change this strong correlation [model (4) and (5)]. So increasing petrol taxes

induces inventors strongly to invest in new technologies, in particular in inventions that reduce fuel use per kilometre driven directly.

Table 6. Empirical Results for Output Technologies

	I	I			
	(1)	(2)	(3)	(4)	(5)
	-2.78 **	-2.99 **	3.52 ***	- 1.64	- 1.40
Standard CO	(1.29)	(1.27)	(0.93)	(1.20)	(1.16)
	-0.97 ***	-0.91 ***	-0.14	-0.56 *	-0.56 *
Standard HC	(0.28) 11.57 ***	(0.27) 11.96 ***	(0.28)	(0.31)	(0.30)
				6.40 ***	5.85 ***
Standard NO _x	(1.85)	(1.83)		(2.30)	(2.20)
	-1.60 ***	-1.75 ***	-0.06	-1.31 ***	-1.24 ***
Standard PM	(0.34)	(0.34)	(0.28)	(0.42)	(0.41)
	0.29		-0.04*	0.18	
Standard FE	(0.51)		(0.60)	(0.56)	
		1.06 *			
Standard FE (low)		(0.54)			
	108.05 ***	103.00 ***	106.34 ***	88.27 ***	73.40 ***
Petrol Tax	(27.62)	(26.55)	(32.54)	(30.10)	(24.52)
	-32.34 ***	-38.25 ***	-17.93	-13.87	
Gasoline Price	(10.10)	(9.63)	(11.58)	(15.91)	
	1.56 ***	1.44 ***	1.77 ***	1.71 ***	1.69 ***
Total patents	(0.26)	(0.25)	(0.30)	(0.39)	(0.35)
•					
Country FE	YES	YES	YES	YES	YES
Time FE	NO	NO	NO	YES	YES
Adj R²	0.66	0.65	0.63	0.80	0.80
Number of obs	108	108	108	108	108
Groups	3	3	3	3	3

All estimations based on OLS with country and time fixed effects.

P-values in parentheses, based on robust standard errors. * p<0.05, ** p<0.01, *** p<0.001.

64. Estimating the sensitivity of patenting of output technologies for the tightening of emission standards produces similar results compared to the patenting of engine redesign technologies at first sight. In this case, however, the results are quite sensitive to multicollinearity problems caused by the in- or exclusion of the NO_x standard. Without this standard, our estimations produce a very simple and intuitive story [see model (3)]. Not only are the other emission standards no longer significant (including those with negative signs), but also the fuel efficiency standard and the CO standard have the expected signs. Also the negative effect from the real petrol price disappears in that case. All of these results do not fundamentally change if we also control for time fixed effects.

7. Conclusions

- 65. Based on a subset of the overall data, this study has shown how important regulatory interventions by governments in Germany, Japan and the US are in inducing serious inventions in the car market. From the previous analysis the following important observations stand out as far as the relative impact of the different types of regulation is concerned:
 - Regulatory pressure is much more important than autonomous and contemporaneous effects from changing net of tax petrol prices. In fact, this study has so far found little evidence for such a

- role, which does not imply that such prices may not have *lagged* effects, for instance because inventors react slowly when they are taken by surprise (rising oil prices are notoriously difficult to predict and therefore, anticipate).
- Furthermore, this study shows some evidence that standards, in particular for CO and to a lesser extent NO_x emissions, strongly correlate with inventions in the main technology groups distinguished in this paper, emission abatement ('emission'), engine redesign ('input') and fuel efficiency ('output') technologies.
- Also petrol taxes seem to have had an impact, in particular on the technologies that increase fuel efficiency. Indeed, such taxes can be anticipated and car companies can present themselves as friends to the consumer by reducing tax payments if they succeed in reducing fuel use.
- Somewhat remarkable is the limited effect observed for fuel efficiency standards. So far these
 standards seem to have had no effect on inventions in fuel efficiency and engine redesign
 technologies. For emission abatement technologies we observe an effect, but only from local
 policies, including negotiated agreements.
- 66 Clearly these conclusions are conditional on further work that should be done. The simplest and clearest observation is that the estimation methodology used so far should be subject to further refinement, like the use of count data methods and the inclusion of other countries from the whole panel. Potentially more important, however, is that new and convincing hypotheses could be built on a deeper analysis of how regulation and technologies are related. Both the technologies involved, as well as the regulatory interventions, have many relevant dimensions that sometimes, but not always, are closely linked. For instance, specific technologies, like OBD systems, had a role when the 3-way catalyst was introduced in 1980s, but such systems became more important for fine-tuning efforts of the combustion process also recently. Also serious trade-offs from a technical point of view are involved. For instance, Figures 2 and 3 that joint reduction of CO and HC is not too difficult, because the formation of these particles is complementary. However, reducing NO_x in addition is less straightforward and optimization of the joint system can only be attained within a narrow band of the air/fuel ratio. Also inventions are mainly limited to specific countries but also easily cross borders as embodied technologies in new car models. In our sample period, the car market changed from what was once mainly a local market to a global market, but with a remarkable concentration of inventions in mainly 3 countries. These examples illuminate that the link between specific emissions, their regulation and technologies invented to reduce emissions is unlikely to be straightforward.
- Finally, there is a whole interesting area yet to be explored, which is how regulators interact and respond to autonomous or regulation-driven changes in the car market. For instance, the growing number of diesel cars in Germany forced the regulators to respond by increasing exhaust regulation, in particular PM, but also seems to have been the result of its own fuel tax policy, with petrol taxes being increased rapidly and diesel taxes staying behind. To what extent this is the outcome of the important invention of the turbo diesel in the beginning of the 1980s is left for further study. Similar examples can be observed in the USA, with its larger cars that escaped strict regulation, and Japan, where lighter cars were build in response to strict urban air quality restrictions. Such considerations should also be linked to the possibility to anticipate (and influence) regulation and taxation, but the impossibility to anticipate unexpected oil price events. These events lend themselves typically for lagged responses and need to be analyzed in further detail as well.

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APPENDIX A³⁷

- 68. This Appendix provides a systematic overview of the IPC classifications related to fuel efficiency measures and automotive emission control technologies. The first section discusses issues related to the use of traditional petroleum-based fuels versus their alternatives, as well as fuel characteristics (additives and composition) which may affect fuel efficiency. This explains which *vehicle design* innovations with implications for fuel efficiency (and thus pollution emissions) we have considered. Measures such as lightweighting of vehicle body materials and improved aerodynamic design are identified. Also adjustments linked to characteristics of the fuels are considered. In the next section the main focus of the patents is the channel which separates emissions from input use (gasoline, diesel) and output (car use), *i.e. emission abatement*. They comprise all technologies that directly reduce emissions (See De Vries, 2007).
- 69. For each major category we first explain the main technology involved. Next we explain the main classification. For example, class F015/00 pertains to patents that deal with 'exhaust or silencing apparatuses.' These are followed by various sub-classifications (N01N5/02 etc.), listed in descending channel of adaptation

A.1 Emissions

70. The first group are typical end-of-pipe *emission abatement* techniques or post-combustion (after-treatment) devices that reduce the amount of emissions per km driven.

A.1.1 Air injection

71. An early approach to CO and HC emissions control involved air injection into an enlarged exhaust manifold to encourage continued oxidation after these gases left the combustion chamber. Air injection as a control method has been discontinued (Masters and Ela 2008).

A.1.2 Catalytic converters (CAT)

- 72. The 1st-generation of catalytic converters were the two-way catalysts [CO,HC], also known as 'oxidation catalysts'. The 2^{nd} -generation of catalysts was capable to control also NO_x emissions, hence three-way catalysts [CO,HC,NO $_x$].
- 73. The emission performance of gasoline (spark-ignition) engines is currently based on a closed-loop fuel mixture in combination with a three-way catalytic converter. Control of the fuel mixture is achieved by means of an oxygen sensor in the exhaust system and an electronic control unit (*e.g.* OBD). Based on the signal from the sensor, the air-to-fuel ratio varies around the stoichiometric value, at which a three-way catalytic converter reaches an optimal efficiency (>99%) (OECD, 2004).

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This section is based on Hascic and Johnstone (2008).

A.1.3 HC adsorbers (CAT)

74. Recently, the three-way catalysts have been accompanied with HC adsorbers in order to control emissions when engine runs at rich mixtures (*e.g.* at cold start, during acceleration).

A.1.4 NO_x adsorbers and de- NO_x systems (CAT)

- 75. Diesel engines are characterised by relatively high emissions of NO_x and PM, requiring application of EGR systems $[NO_x]$, recently complemented with additional NO_x adsorbers (NO_x) traps) or lean NO_x catalysts (de- NO_x systems, de- NO_x converters).
- 76. Since diesel vehicles run on lean fuel mixture, they cannot use the three-way catalytic converters because three-way catalytic converters require stoichiometric (not lean) fuel mixture. Consequently, 'one-way' catalysts (known as lean NO_x catalysts, de- NO_x systems, or de- NO_x converters) have been applied instead. These involve passive or active de- NO_x catalysts, selective catalytic reduction (SCR) catalysts, or NO_x storage catalysts.³⁸

A.1.5 Diesel oxidation catalysts

77. While emissions of CO and HC from diesel engines are relatively low, introduction of strict emissions limits even for diesel cars necessitated the use of oxidation catalysts which can reduce these emissions to near zero levels. However, HC emissions can be significant during cold start conditions.

A.1.6 Positive crankcase ventilation (CRK)

78. During the power and compression strokes, certain amount of combustion gases (HCs) finds their way around the piston into the crankcase. In the past, this "blowby" used to be vented directly into the atmosphere. Positive crankcase ventilation is a method to recycle blowby gases back into the engine air intake system to give it a second chance at being burned and released into the exhaust system, while maintaining the desired air-fuel ratio (Masters and Ela, 2008).

A.1.7 Thermal reactor (THR)

79. An early control method; composed of an after-burner that encourages the continued oxidation of CO and HC after these gases have left the combustion chamber.

A.1.8 Exhaust gas recirculation (EGR)

80. An early approach to NO_x control was to recirculate a portion of the exhaust gas back into the incoming air-fuel mixture, thus decreasing combustion temperature (this relatively inert gas absorbs some of the heat without affecting the air-fuel ratio), and hence reducing the production of NO_x . Controlling NOx via EGR is becoming less common (Masters and Ela, 2008).

They can be used also with lean-burn gasoline engines instead of catalytic converters.

Catalytic converters, lean NO_X catalysts, NO_X adsorbers, regeneration (CAT)								
B01D 53/92	Processes, apparatus or devices specially adapted for purification of engine exhaust gases [6]							
B01D 53/94	by catalytic processes [6]							
B01D 53/96	Regeneration, reactivation or recycling of reactants [6]							
B01J 23/38-46	Catalysts comprising metals or metal oxides or hydroxides; of noble metals; of the platinum group metals [2]							
F01N 3/05	Exhaust or silencing apparatus having means for purifying, rendering innocuous, or otherwise treating exhaust by means of air <i>e.g.</i> by mixing exhaust with air.							
F01N 3/08-34	Exhaust or silencing apparatus having means for purifying, rendering innocuous, or otherwise treating exhaust; for rendering innocuous by thermal or catalytic conversion of noxious components of exhaust							
	Crankcase emissions and control (CRK)							
F01M 13/02-04	Crankcase ventilating or breathing [2]							
	Thermal reactor (THR)							
F01N 3/26	Exhaust apparatus having means for rendering innocuous, by thermal conversion of noxious components of exhaust; Construction of thermal reactors [3]							
	Exhaust Gas Recirculation (EGR)							
F01N 5/00	Exhaust or silencing apparatus combined or associated with devices profiting by exhaust energy							
F02B 47/08-10	Methods of operating engines involving adding non-fuel substances including exhaust gas to combustion air, fuel, or fuel-air mixtures of engines							
F02D 21/06-10	Controlling engines characterised by their being supplied with non-fuel gas added to combustion-air, such as the exhaust gas of engine, or having secondary air added to fuel-air mixture							
F02M 25/07	Engine-pertinent apparatus for adding exhaust gases to combustion-air, main fuel, or fuel-air mixture [5]							

A.2 Input: fuels

81. The second group is typically related to the characteristics of the fuels and the additives used to enhance productivity and emission intensity of the combustion process.

A.2.1 Anti-knock additives (AKA)

82. In the past, various lead-containing additives (*e.g.*, tetraethyl lead) were used because this was the most cost-effective way of boosting the octane levels (see *e.g.*, Kerr and Newell 2003). However, environmental and health considerations of lead-related air pollutants as well as the incompatibility of lead with the use of catalytic converters, spurred the search for alternatives.³⁹ Initially, certain aromatic hydrocarbons (incl. benzene and its derivatives toluene and xylene, or BTX) were introduced as alternative octane-enhancers. However, these volatile hydrocarbons have a high photo-chemical reactivity. As a result,

39

Isomerisation allows producing high-octane blending components (isomers) and hence represents an alternative approach to adding fuel additives. Isomerisation is a process of altering hydrocarbon molecules to produce compounds (*e.g.*, isopentane, isohexane) which have higher octane rating; it does not involve adding or removing any substances (see *e.g.*, Pellegrino 2007). For example, the switch from leaded to unleaded gasoline in the United States was, to a large degree, possible due to the commercialisation of pentane-hexane isomerisation technology which allowed boosting octane levels without using lead additives (Kerr and Newell 2003).

increasing their proportion in gasoline blends also increased evaporative emissions (HC) and the formation of VOCs and photochemical (ozone) smog (Masters and Ela 2008).⁴⁰ To reduce the volatility of gasoline fuels, many countries introduced limits on gasoline aromatics and substituted them with alternatives, such as ethers (*e.g.*, MTBE or ETBE) or alcohols (*e.g.*, methanol or ethanol). In the United States, MTBE has been the preferred alternative due to its higher octane ranking and lower cost (USEPA 2007). Recently, MTBE has started to be phased-out in the United States and replaced by other ethers (*e.g.*, ETBE) or alcohols (*e.g.*, ethanol).

A.2.2 Oxygen-containing additives (OKA)

- 83. Burning 'oxygenated' (also known as reformulated) gasoline encourages more complete combustion. The use of oxygen-containing additives was thus primarily aimed at reducing tailpipe emissions of carbon monoxide (CO) and unburned fuel (HC). Examples of such additives include alcohols (e.g., methanol and ethanol) or ethers [e.g., methyl tertiary-butyl ether (MTBE), ethyl tertiary-butyl ether (ETBE), tertiary amyl methyl ether (TAME), and diisopropyl ether (DIPE)].
- 84. In the United States, MTBE has been used since 1979 initially at low concentrations to replace lead as an octane enhancer. Since 1992 it has been used at higher concentrations to meet the oxygenate requirements set by the 1990 Clean Air Act amendment⁴¹ (USEPA, 2007). Until recently, MTBE has been the most common oxygenate additive, followed by ethanol (Pellegrino *et al.*, 2007). MTBE has been credited for contributing to reducing CO emissions (as oxygenate) and VOC/ozone pollution levels (as oxygenate as well as by replacing aromatics as octane enhancers) (USGS, 2007).
- 85. However, due to concerns over drinking water contamination and potential negative health effects, the use of MTBE has become increasingly controversial. Twenty-five U.S. states have mandated reduction or elimination of MTBE (incl. California where it has been banned since 2003) and suppliers have begun replacing it with ethanol. In addition, the Energy Policy Act of 2005 removed the fuel oxygenate requirements (Pellegrino *et al.*, 2007). It is expected that most suppliers will have phased-out MTBE by summer 2006 (EIA 2006). MTBE is being replaced by ethanol, and to a lesser extent, by the ethanol-derived ETBE.
- 86. In sum, some compounds, such as alcohols and ethers, can be used to both, oxygenate the fuel blend (and reduce CO and HC emissions) as well as to increase its octane rating (thus replace VOC & ozone-forming aromatics). We also note that adding oxygenates to fuel blends may increase fuel combustion. This is because while adding oxygen to fuel blends improves combustion efficiency, it also increases fuel volume without contributing energy. Consequently, adding oxygenate compounds may actually increase fuel combustion for a given power output. Whether this will be the case depends on the relative contribution of improved combustion versus lower energy-content of the fuel.

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Other alternatives included methylcyclopentadienyl manganese tricarbonyl (known as MMT) used in the United States (until banned in 1977 due to health concerns, and again re-authorized in 1995), and other countries such as Canada and Australia (see *e.g.*, Masters and Ela 2008).

The U.S. Clean Air Act introduced a 2% (by weight) oxygen requirement in fuels used in areas that have high levels of CO pollution (non-attainment zones), starting in 1992. In the United States, higher octane number and lower volatility of MTBE compared to ethanol made it the preferred option.

Anti-knock additives (octane-enhancers) (AKA)								
C10L 10/10	Use of additives to fuels or fires for improving the octane number [8]							
	Oxygen-containing additives (OCA)							
C10L 10/10	C10L 10/10 Use of additives to fuels or fires for improving the octane number [8]							
Note: Ideally, oxygen-related patents would be extracted from classes C10L 10/00 or C10L 1/10-30.								
Instead, the above	e is used as a proxy, since it relates more-less to the same chemical compounds.							

A.3 Input: combustion

87. Third, we consider a whole set technologies that typically involve engine redesign, *e.g.* through the introduction of combustion technologies that require less fuel per kilometre driven and therefore reduce emissions per km.

A.3.1 Fuel injection (FIN)

A.3.2 Sensors (SRS)

A.3.3 Electronic control systems (OBD)

88. Introduction of the three-way catalytic converter required the development of precise electronic feedback control systems (*e.g.*, OBD) that monitor the composition of exhaust gases and feed that information to a microprocessor-controlled carburettor or fuel-injection system (Masters and Ela 2008). Development of such 'closed-loop' systems with a high degree of control was necessary for the three-way catalytic converters to operate effectively. This is because they must operate within a very narrow band of air-fuel ratios near the stoichiometric value (see Figure 2).

A.3.4 Ignition timing (IGT)

89. In addition to controlling the air-fuel mixture, another method for reducing emissions from spark ignition engines is by careful control of ignition timing. Retarding ignition timing from the best efficiency setting reduces HC and NOx emissions, while excessive retard of ignition increases the output of CO and HC. Increasing engine speed reduces HC emissions, but NOx emissions increase with load. Increasing coolant temperature tends to reduce HC emissions, but this results in an increase in NOx emissions [citation].

A.3.5 Other factors related to engine design (AFR?)

90. Other factors which influence fuel economy and production of pollutants during combustion include variable valve timing, variable compression ratio, combustion chamber geometry, as well as performance during vehicle idling, accelerating, cruising, and decelerating. See also cold start⁴² and start-stop modes (for further info see *e.g.*, IEA 2005: 45-46, 65).

A.3.6 Combustion air & fuel conditioning (FHR)

91. Recently, fuel conditioning systems have been introduced to improve combustion with the aim of reducing fuel consumption (and hence emissions), *e.g.* by pre-treatment of fuel by chemical, electric,

Catalytic converters are most efficient when heated up to >300-350°C. Consequently, the amount of pollutants emitted at cold start may be very high.

magnetic, or radiation means. The aim (of heating, reforming, or activating) is to increase fuel temperature, increase fuel vaporization, or change fuel properties, immediately before combustion takes place [citation].

	Fuel injection systems (FIN)								
	Arrangements of fuel-injection apparatus with respect to engines; Pump drives								
F02M 39/00	adapted top such arrangements								
E02M 41/00	Fuel-injection apparatus with two or more injectors fed from a common pressure-								
F02M 41/00	source sequentially by means of a distributor								
F02M 43/00	Fuel-injection apparatus operating simultaneously on two or more fuels or on a								
1 02111 13/00	liquid fuel and another liquid, e.g. the other liquid being an anti-knock additive								
F02M 45/00	Fuel-injection apparatus characterized by having a cyclic delivery of specific time/pressure or time/quantity relationship								
F02M 47/00	Fuel-injection apparatus operated cyclically with fuel-injection valves actuated by								
102111 17700	fluid pressure								
F023 4 40/00	Fuel-injection apparatus in which injection pumps are driven, or injectors are								
F02M 49/00	actuated, by the pressure in engine working cylinders, or by impact of engine working piston								
F02M 51/00	Fuel injection apparatus characterized by being operated electrically								
	Fuel-injection apparatus characterized by having heating, cooling, or thermally-								
F02M 53/00	insulating means								
F02M 55/00	Fuel-injection apparatus characterized by their fuel conduits or their venting								
	means								
F02M 57/00	Fuel injectors combined or associated with other devices								
F02M 59/00	Pumps specially adapted for fuel-injection and not provided for in groups F02M 39/00 to F02M 57/00								
F02M 61/00	Fuel injection not provided for in groups F02M 39/00 to F02M 57/00								
F02M 63/00	Other fuel-injection apparatus, parts, or accessories having pertinent characteristics not provided for								
F02M 65/00	Testing fuel-injection apparatus, e.g. testing injection timing								
F02M 69/00	Low-pressure fuel-injection apparatus								
F02M 71/00	Combinations of carburettors and low-pressure fuel-injection apparatus								
	Oxygen, NOX and temperature sensors (SRS)								
F01N 11/00	Monitoring or diagnostic devices for exhaust-gas treatment apparatus								
G01M 15/10	Testing of internal-combustion engines by monitoring exhaust gases								
	Electronic control systems (OBD)								
F01N 9/00	Electrical control of exhaust gas treating apparatus [4]								
F02D 41/00	Electrical control of supply of combustible mixture or its constituents [4]								
F02D 43/00	Conjoint electrical control of two or more functions, <i>e.g.</i> ignition, fuel-air mixture, recirculation, supercharging, exhaust-gas treatment [4]								
F02D 45/00	Electrical control of combustion engines not provided for in groups F02D 41/00 to F02D 43/00 [4]								
	Ignition timing (IGT)								
F02P 5/00	Advancing or retarding ignition; Control therefore [6]								
	Devices for fuel heating, reforming, or activation (FHR)								
F02M 27/00	Apparatus for treating combustion-air, fuel, or fuel-air mixture, by catalysts, electric means, magnetism, rays, sonic waves, or the like								
F02M 31/02-18	Apparatus for thermally treating combustion-air, fuel, or fuel-air mixture								

A.4 Output: fuel efficiency

92. Finally, we include counts of typical technologies that improve *fuel efficiency* through alternative design of cars, like their aerodynamics, or other characteristics such as tyre resistancy. Other factors, related to vehicle design more broadly, may have an important effect on vehicle fuel consumption. This includes reducing the friction of moving and/or rotating components (*e.g.*, components of the engine and the gearbox, transmission, wheels) by optimized shape/geometry of the combustion chamber and intake/outlet ports/valves, as well as the use of low-friction materials.

A.4.1 Air resistance (ARS)

93. Fuel efficiency improvements can also be achieved by reducing the energy requirements necessary to overcome the air resistance (aerodynamic drag) by streamlining the shape of the vehicle and its frontal area, as well as any reducing drag caused by windows and luggage carriers (aerodynamic design).

A.4.2 Rolling resistance (RRS)

94. Measures intended to reduce energy required to overcome the rolling resistance (incl. tire quality, tire pressure) (for further info, see OECD 2004: 136-138).

A.4.3 Auxiliary systems

95. Operating auxiliary systems and vehicle accessories (such as lighting, air conditioning and heating, power steering) may contribute significantly to increased fuel consumption and pollution emissions. For example, the estimated effect of usage of AC systems under typical European conditions on fuel consumption varies between less than 1% (Hugruel 2004) and 4-8% (ECCP 2003) (see Roujol 2005 for citations).

A.4.4 Other fuel-saving driver support devices (FSS)

96. Devices that improve comfort and/or driving style, and may affect fuel consumption, include *e.g.* speed (cruise) control systems and its modifications, such as adaptive cruise control (eco-driving). For more see IEA (2005: 57-58).

Air resistance (aerodynamic design) (ARS)									
B62D 35/00	Vehicle bodies characterised by streamlining								
B62D 37/02	Stabilising vehicle bodies without controlling suspension arrangements; by aerodynamic means								
Rolling resistance (tyres) (RRS)									
B60C 23/00	Devices for measuring, signalling, controlling, or distributing tyre pressure or temperature, specially adapted for mounting on vehicles; Arrangement of tyre inflating devices on vehicles, <i>e.g.</i> of pumps, of tanks; Tyre cooling arrangements [3]								
	Other fuel-efficiency support systems (FSS)								
B60T 1/10	Arrangements of braking elements; acting by retarding wheels; by utilising wheel movement for accumulating energy, <i>e.g.</i> driving air compressors								
B60G 13/14	Resilient suspensions characterised by arrangement, location, or type of vibration-dampers; having dampers accumulating utilisable energy, <i>e.g.</i> compressing air								
B60K 31/00	Vehicle fittings, acting on a single sub-unit only, for automatically controlling vehicle speed, <i>i.e.</i> preventing speed from exceeding an arbitrarily established velocity or maintaining speed at a particular velocity, as selected by the vehicle operator								
B60W 30/10-20	Purposes of road vehicle drive control systems not related to the control of a particular sub-unit, <i>e.g.</i> of systems using conjoint control of vehicle sub-units (incl. path keeping, cruise control) [8]								

APPENDIX B. EMISSION STANDARDS FOR CARBON MONOXIDE, HYDROCARBONS, NITROGEN OXIDES AND PARTICULATE MATTER (GRAMS PER KILOMETER)

COUNTRY	US	JPN	JPN	EUR	EUR	
POLLUTANT	СО	co	СО	СО	СО	
FUEL	all fuels	petrol	diesel	petrol	diesel	
1970	54.72					
1971	54.72			37.51		
1972	45.06			37.51		
1973	45.06	18.4		37.51		
1974	45.06	18.4	790ppm	37.51		
1975	24.14	2.10(60.0g/test)	790ppm	30.11		
1976	24.14	2.10(60.0g/test)	790ppm	30.11		
1977	24.14	2.10(60.0g/test)	790ppm	30.11		
1978	24.14	2.10(60.0g/test)	790ppm	30.11		
1979	24.14	2.10(60.0g/test)	790ppm	30.11	-	
1980	11.27	2.10(60.0g/test)	790ppm	30.11	-	
1981	5.47	2.10(60.0g/test)	790ppm	30.11	ı	
1982	5.47	2.10(60.0g/test)	790ppm	30.11	-	
1983	5.47	2.10(60.0g/test)	790ppm	30.11	ı	
1984	5.47	2.10(60.0g/test)	790ppm	18.76	18.76	
1985	5.47	2.10(60.0g/test)	790ppm	18.76	18.76	
1986	5.47	2.10(60.0g/test)	2.10	18.76	18.76	
1987	5.47	2.10(60.0g/test)	2.10	18.76	18.76	
1988	5.47	2.10(60.0g/test)	2.10	18.76	18.76	
1989	5.47	2.10(60.0g/test)	2.10	7.40	7.40	
1990	5.47	2.10(60.0g/test)	2.10	7.40	7.40	
1991	5.47	2.10(60.0g/test)	2.10	7.40	7.40	
1992	5.47	2.10(60.0g/test)	2.10	2.72	2.72	
1993	5.47	2.10(60.0g/test)	2.10	2.72	2.72	
1994	5.47	2.10(60.0g/test)	2.10	2.72	2.72	
1995	5.47	2.10(60.0g/test)	2.10	2.72	2.72	
1996	5.47	2.10(60.0g/test)	2.10	2.20	1.00	
1997	5.47	2.10(60.0g/test)	2.10	2.20	1.00	
1998	5.47	2.10(60.0g/test)	2.10	2.20	1.00	
1999	5.47	2.10(60.0g/test)	2.10	2.20	1.00	
2000	5.47	0.67(19.0g/test)	2.10	2.30	0.64	
2001		0.67(19.0g/test)	2.10	2.30	0.64	
2002		0.67(19.0g/test)	0.63	2.30	0.64	
2003		0.67(19.0g/test)	0.63	2.30	0.64	
2004		0.67(19.0g/test)	0.63	2.30	0.64	
2005		1.15 i)	0.63	1.00	0.50	

Figures inside parentheses indicate limit values based on cold start test mode.

COM/ENV/EPOC/CTPA/CFA(2008)32/FINAL

COUNTRY	US	US	US	US	US	JPN	JPN	JPN	JPN
POLLUTANT	НС	NOx	NOx	NOx	HC+NOx	НС	НС	NOx	NOx
FUEL	all fuels	petrol	diesel	all fuels	all fuels	petrol	diesel	petrol	Diesel
1970	6.60				6.60				
1971	6.60				6.60				
1972	4.83				4.83				
1973	4.83			4.99	9.82	2.94		2.18	
1974	4.83			4.99	9.82	2.94	510ppm	2.18	450ppm
1975	2.41			4.99	7.40	0.25(7.00g/test)	510ppm	1.20(9.00g/test)	450ppm
1976	2.41	4.99	4.99	4.99	7.40	0.25(7.00g/test)	510ppm	0.6 0(6.00g/test)	450ppm
1977	2.41	3.22	3.22	3.22	5.63	0.25(7.00g/test)	510ppm	0.60(6.00g/test)	380ppm
1978	2.41	3.22	3.22	3.22	5.63	0.25(7.00g/test)	510ppm	0.25 (4.40g/test)	380ppm
1979	2.41	3.22	3.22	3.22	5.63	0.25(7.00g/test)	510ppm	0.25(4.40g/test)	340ppm
1980	0.66	3.22	3.22	3.22	3.88	0.25(7.00g/test)	510ppm	0.25(4.40g/test)	340ppm
1981	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	510ppm	0.25(4.40g/test)	340ppm
1982	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	510ppm	0.25(4.40g/test)	290ppm
1983	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	510ppm	0.25(4.40g/test)	290ppm
1984	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	510ppm	0.25(4.40g/test)	290ppm
1985	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	510ppm	0.25(4.40g/test)	290ppm
1986	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	0.40 d)	0.25(4.40g/test)	0.90
1987	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.90
1988	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.90
1989	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.90
1990	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.90
1991	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.90
1992	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.60
1993	0.66	1.61	1.61	1.61	2.27	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.60
1994	0.40	0.64	1.61	0.64	1.05	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.60
1995	0.40	0.64	1.61	0.64	1.05	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.60
1996	0.40	0.64	1.61	0.64	1.05	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.60
1997	0.40	0.64	1.61	0.64	1.05	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.60
1998	0.40	0.64	1.61	0.64	1.05	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.40
1999	0.40	0.64	1.61	0.64	1.05	0.25(7.00g/test)	0.40	0.25(4.40g/test)	0.40
2000	0.40	0.64	1.61	0.64	1.05	0.08(2.20g/test)	0.40	0.08(1.40g/test)	0.40
2001						0.08(2.20g/test)	0.40	0.08(1.40g/test)	0.40
2002						0.08(2.20g/test)	0.12	0.08(1.40g/test)	0.30
2003						0.08(2.20g/test)	0.12	0.08(1.40g/test)	0.30
2004						0.08(2.20g/test)	0.12	0.08(1.40g/test)	0.30
2005						0.05	0.024	0.05	0.15

COM/ENV/EPOC/CTPA/CFA(2008)32/FINAL

COUNTRY	EUR	EUR	EUR	EUR	EUR	EUR	US	JPN	EUR
POLLUTANT	НС	НС	NOx	NOx	HC+NOx	HC+NOx	PM	PM	PM
FUEL	petrol	diesel	petrol	diesel	petrol	diesel	all fuels	Diesel	diesel
1970									
1971	2.49			-	1			-	
1972	2.49			-	1	-			
1973	2.49				1				
1974	2.49								
1975	2.12								
1976	2.12								
1977	2.12								
1978	2.12								
1979	2.12								
1980	2.12								
1981	2.12				-				
1982	2.12								
1983	2.12				-				
1984					5.43	5.43			
1985					5.43	5.43			
1986					5.43	5.43			
1987					5.43	5.43			
1988					5.43	5.43			
1989					1.97	1.97			
1990					1.97	1.97			0.27
1991					1.97	1.97			0.27
1992					0.97	0.97			0.14
1993					0.97	0.97			0.14
1994					0.97	0.97		0.20	0.14
1995					0.97	0.97	0.13	0.20	0.14
1996					0.50	0.70	0.13	0.20	0.08
1997					0.50	0.70	0.13	0.08 d)	0.08
1998					0.50	0.70	0.13	0.08	0.08
1999					0.50	0.70	0.13	0.08	0.08
2000	0.20		0.15	0.50		0.56	0.13	0.08	0.05
2001	0.20		0.15	0.50		0.56		0.08	0.05
2002	0.20		0.15	0.50		0.56		0.056	0.05
2003	0.20		0.15	0.50		0.56		0.056	0.05
2004	0.20		0.15	0.50		0.56		0.056	0.05
2005	0.10		0.08	0.25		0.30		0.014	0.03

APPENDIX C. PATENT COUNTS FOR MAJOR MOTOR VEHICLE EMISSION CONTROL AND FUEL EFFICIENCY MEASURES IN 31 COUNTRIES 1965-2005

	Emissions				Input (fuel)	Input (engine)							t (fuel effi	Total		
Country	CAT	FHR	CRK	THR	OCA/AKA	AFR	SRS	FIN	EGR	OBD	IGT	ARS	RRS	FSS	#	%
US	1677.1	381.3	74.6	28.0	18.7	786.6	166.2	1613.8	466.2	1928.9	352.6	100.8	375.3	226.8	8196.9	13.7
JP	4511.1	426.5	167.7	60.2	11.0	2582.7	321.8	3414.1	1583.7	######	1908.3	88.0	510.9	1019.9	28212.5	47.2
DE	2796.1	343.3	170.6	51.5	8.0	1019.4	406.7	4856.9	752.3	4706.3	518.0	155.2	453.4	689.7	16927.5	28.3
AT	38.5	11.0	2.4	0.5	0.0	39.3	9.2	227.8	29.6	95.3	4.9	8.2	9.5	6.9	483.1	0.8
AU	2.2	3.0	0.0	0.0	0.0	13.7	0.0	15.4	1.0	12.5	3.0	2.0	4.0	1.5	58.3	0.1
BE	24.4	0.2	0.0	0.0	0.0	10.0	1.8	6.1	3.8	12.8	0.2	2.0	2.5	1.3	65.1	0.1
CA	51.5	24.6	2.0	0.0	0.2	107.8	5.0	41.5	46.5	35.2	8.7	16.0	21.1	7.0	367.1	0.6
СН	38.6	8.7	0.5	2.0	0.0	25.7	2.6	65.6	9.5	26.0	1.0	0.3	10.8	0.7	192.0	0.3
DK	21.2	4.5	0.0	0.0	1.0	12.8	0.0	48.6	11.0	11.0	2.0	2.0	3.0	1.0	118.1	0.2
ES	9.6	12.2	0.0	1.0	0.0	22.5	0.0	18.8	8.6	9.8	0.1	2.0	10.1	2.0	96.7	0.2
FI	59.3	6.0	1.0	2.0	0.0	21.5	0.8	37.9	10.0	6.1	0.0	2.0	7.0	2.0	155.6	0.3
FR	608.6	93.4	10.0	5.0	2.2	204.4	83.5	391.5	181.0	570.9	86.0	36.1	226.1	51.8	2550.6	4.3
GB	126.3	32.2	11.0	1.3	0.0	84.9	6.8	119.8	61.9	132.4	25.6	12.0	21.2	22.7	658.2	1.1
GR	3.5	4.0	0.0	0.0	0.0	7.9	0.0	0.3	3.0	2.3	0.0	0.0	5.0	0.0	26.1	0.0
IT	116.9	36.9	9.0	5.0	1.9	50.7	10.2	274.5	29.8	208.6	37.7	19.0	46.4	20.2	866.8	1.4
LU	4.8	1.0	0.0	0.0	0.0	3.3	2.0	8.4	3.0	17.4	1.5	0.0	2.7	1.0	45.1	0.1
NL	46.3	10.0	0.0	0.5	0.0	8.9	5.2	25.3	3.7	16.4	2.0	0.0	5.1	3.7	127.1	0.2
NO	6.0	2.0	0.0	0.0	0.0	4.0	0.0	2.7	1.0	1.0	0.0	0.0	5.0	1.0	22.7	0.0
SE	121.1	19.7	22.0	2.6	0.0	91.6	12.0	55.3	82.2	166.8	21.0	14.3	8.0	40.3	657.0	1.1
Total	10263.1	1420.5	470.8	159.6	43	5097.7	1033.8	11224.3	3287.8	19566	2972.6	459.9	1727.1	2099.5	59826.5	100
%	17.2	2.4	0.8	0.3	0.1	8.5	1.7	18.8	5.5	32.7	5	0.8	2.9	3.5	100	